Recent results and future prospects from Super-Kamiokande

Yasuhiro Nakajima (ICRR, the University of Tokyo)
on behalf of the Super-Kamiokande collaboration

NEUTRINO
2020

The Super-Kamiokande Collaboration

~190 collaborators from 49 institutes in 10 countries

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan	INFN Roma, Italy	University of Sheffield, UK
RCCN, ICRR, Univ. of Tokyo, Japan	Kavli IPMU, The Univ. of Tokyo, Japan	Shizuoka University of Welfare, Japan
University Autonoma Madrid, Spain	Keio University, Japan	Sungkyunkwan University, Korea
BC Institute of Technology, Canada	KEK, Japan	Stony Brook University, USA
Boston University, USA	King's College London, UK	Tokai University, Japan
University of California, Irvine, USA	Kobe University, Japan	The University of Tokyo, Japan
California State University, USA	Kyoto University, Japan	Tokyo Institute of Technology, Japan
Chonnam National University, Korea	University of Liverpool, UK	Tokyo University of Science, japan
Duke University, USA	LLR, Ecole polytechnique, France	University of Toronto, Canada
Fukuoka Institute of Technology, Japan	Miyagi University of Education, Japan	TRIUMF, Canada
Gifu University, Japan	ISEE, Nagoya University, Japan	Tsinghua University, Korea
GIST, Korea	NCBJ, Poland	University of Warsaw, Poland
University of Hawaii, USA	Okayama University, Japan	Warwick University, UK
Imperial College London, UK	University of Oxford, UK	The University of Winnipeg, Canada
INFN Bari, Italy	Queen Mary University of London, UK	Yokohama National University, Japan
INFN Napoli, Italy	Rutherford Appleton Laboratory, UK	
INFN Padova, Italy	Seoul National University, Korea	

Super-Kamiokande

41.4 m

39.3 m
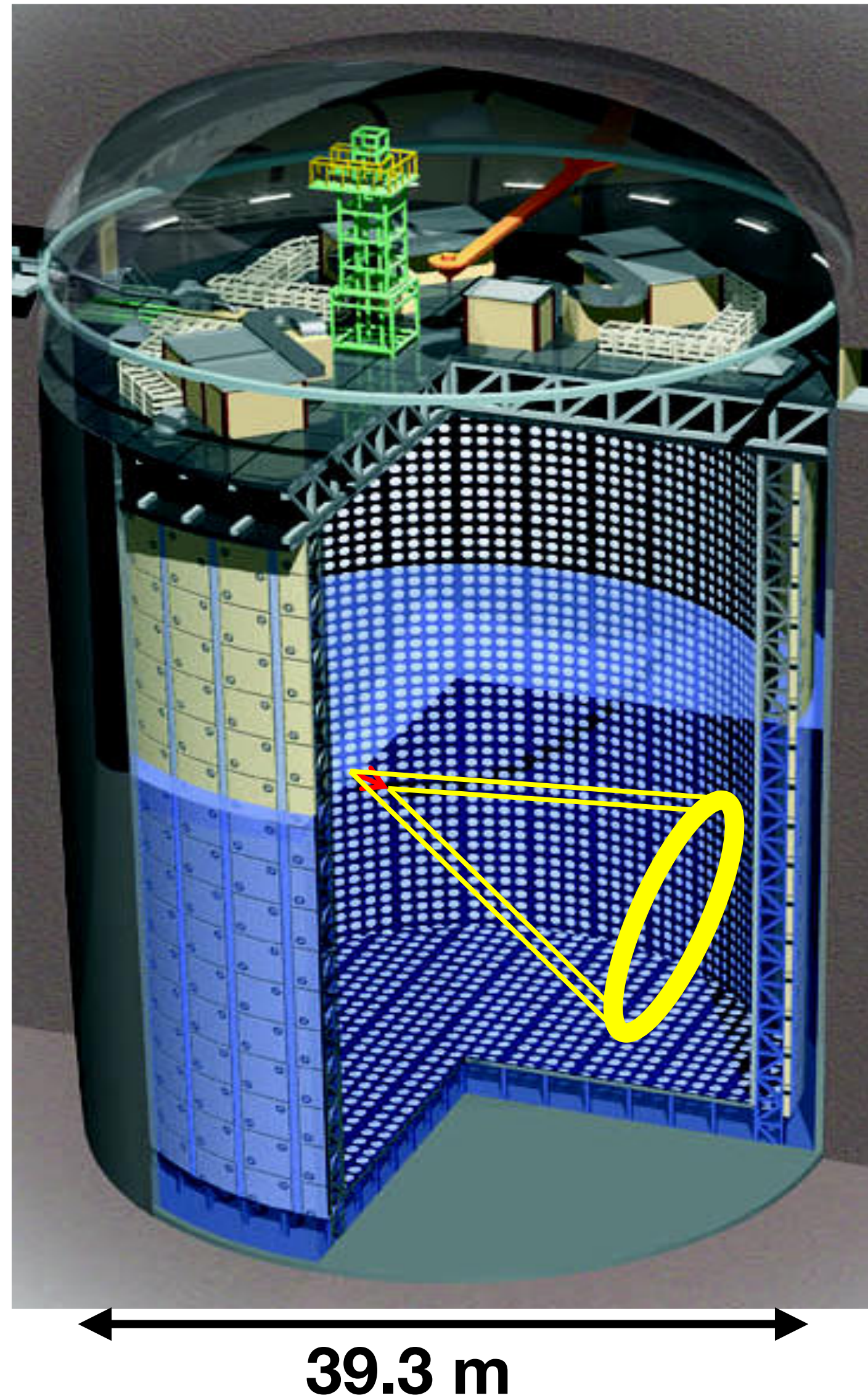
- 50-kton water Cherenkov detector located at Kamioka, Japan

- Overburden: 2700 mwe

- Inner Detector covered by > 11000 20-inch PMTs

- Studying neutrinos from wide variety of sources

  - Solar neutrinos

  - Supernova neutrinos   **~ MeV**

  - Atmospheric/Accelerator neutrinos   **~ GeV**

- Operational since 1996, transitioning to SK-Gd

1996   2002   2006 2008   2018   2019

| SK-I | SK-II | SK-III | SK-IV | SK-V | SK-Gd |

Photo coverage 40%   20%   40%   40%   40%

Accident   Full reconstruction   Replace electronics & DAQ system   Tank refurbishment
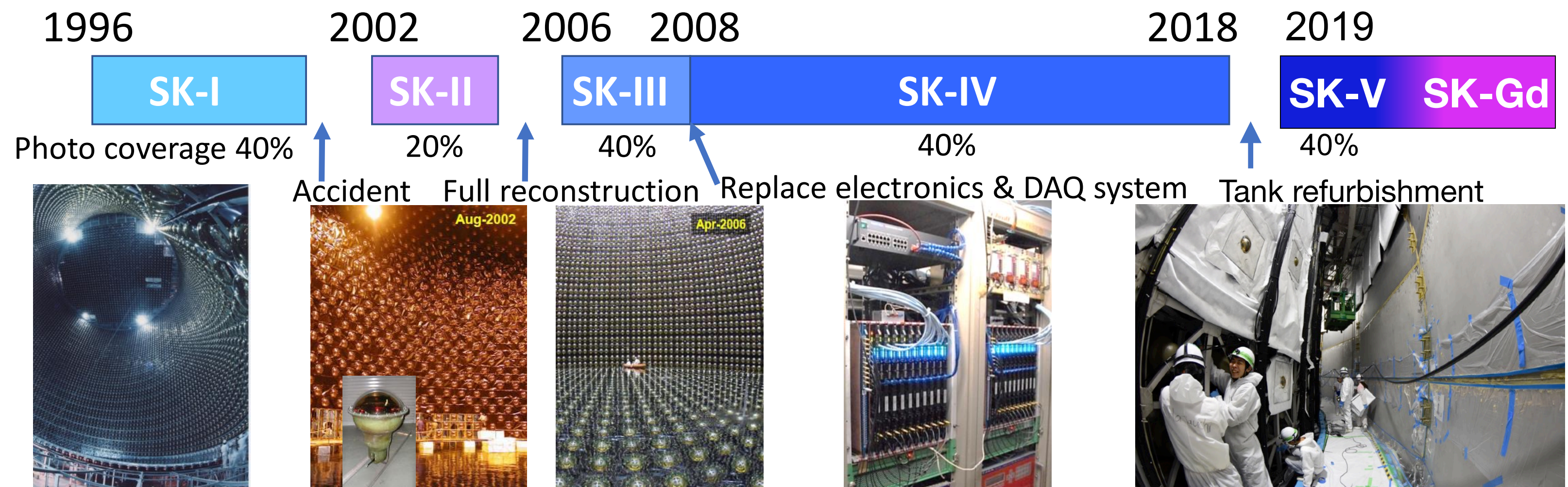
# Super-Kamiokande Gadolinium Project (SK-Gd)

- Dissolving Gd to Super-Kamiokande to significantly enhance detection capability of neutrons from ν interactions

  J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. 93 (2004) 17110

- Aiming for the **first observation of Diffuse Supernova Neutrino Backgrounds**

- Also aiming for:

  - Improving pointing accuracy for galactic supernova

  - Precursor of nearby supernova by Si-burning neutrinos

  - Reducing proton decay background

  - Neutrino/anti-neutrino discrimination (Long-baseline and atmospheric neutrinos)

  - Reactor neutrino measurements

- As the first step, loading 0.02% of $Gd_2(SO_4)_3$ in 2020

  ~50% n-capture on Gd
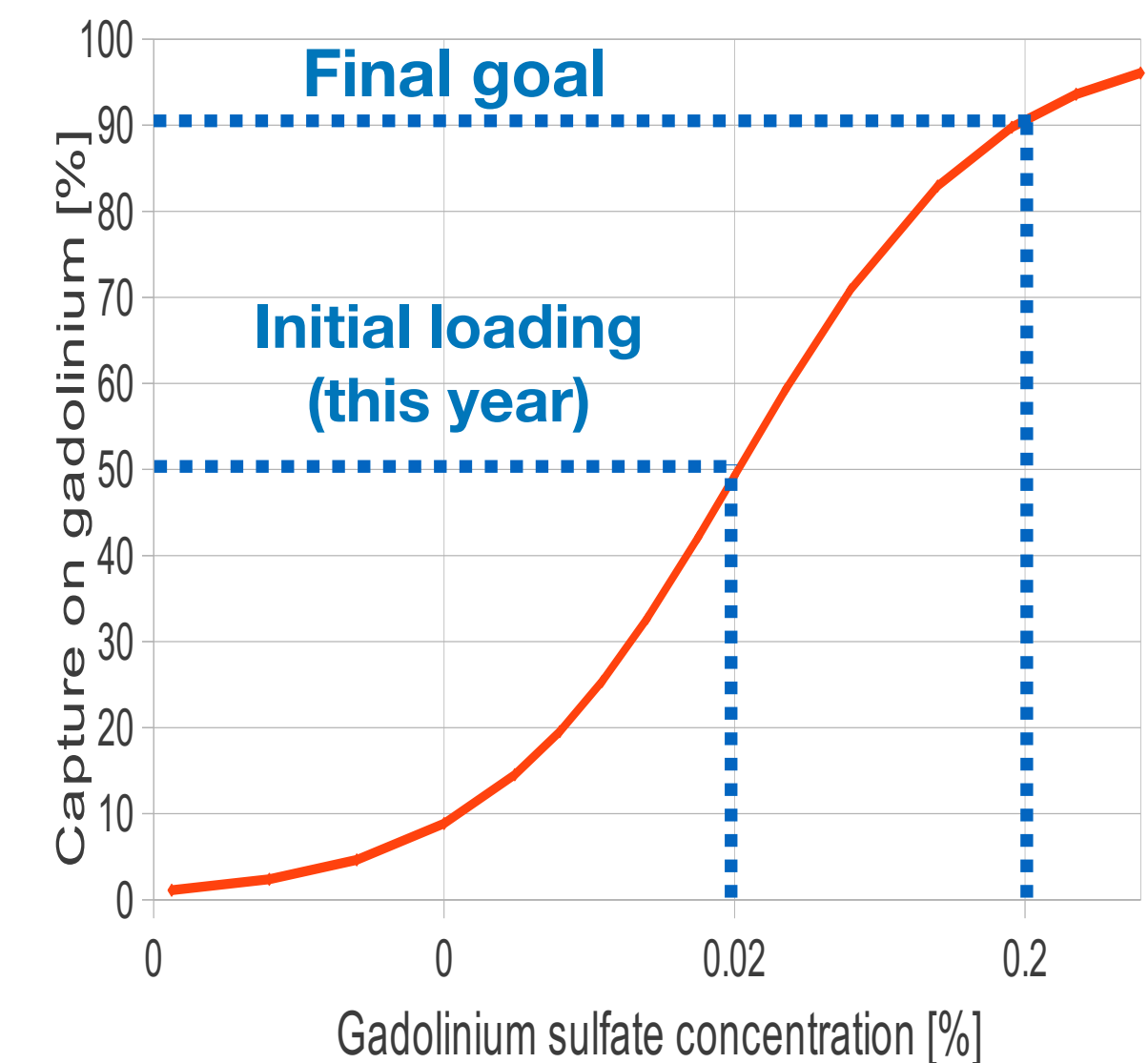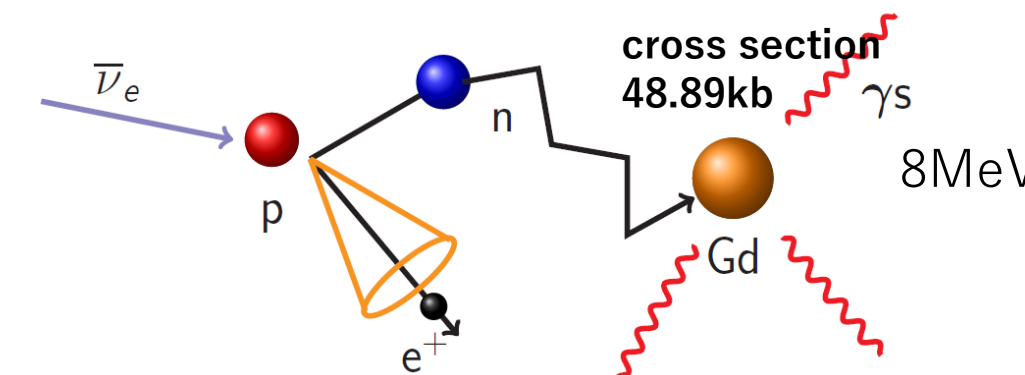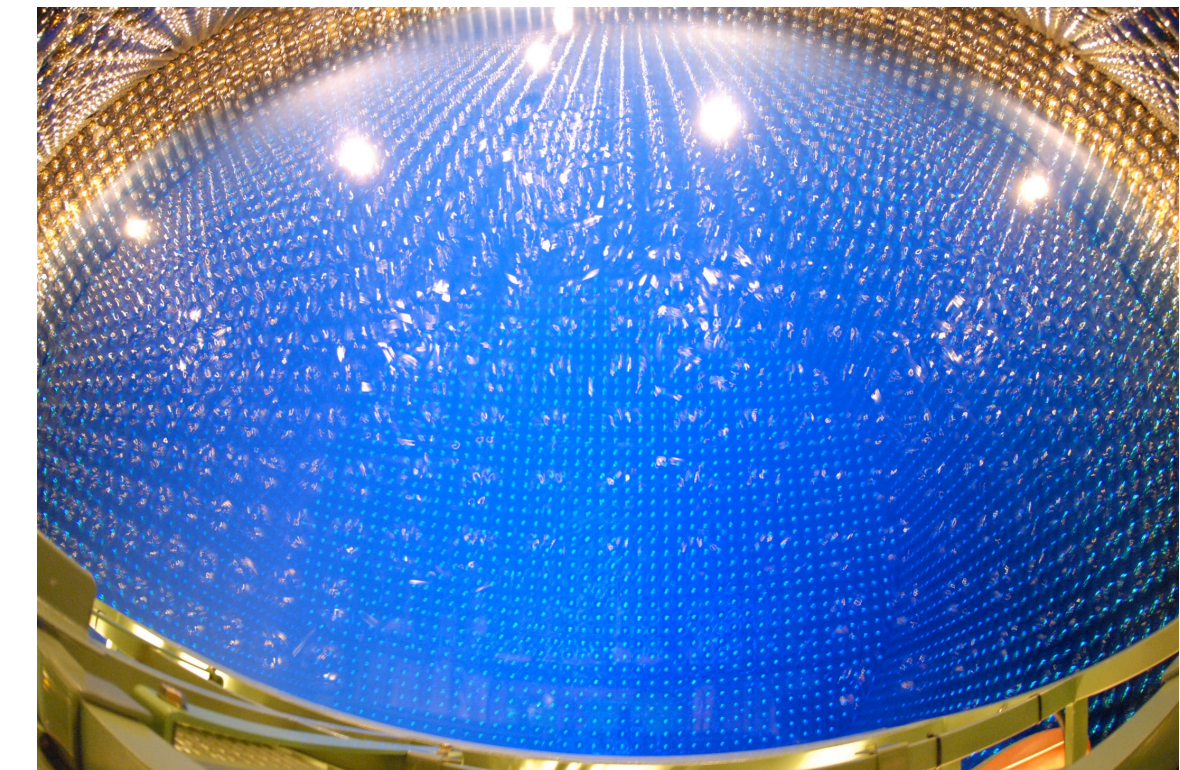
R&D Challenges (RI in Gd powder)

- Radio impurities in Gd power could introduce additional backgrounds to solar and supernova neutrinos

- Stringent requirement for RI imposed

- Developed methods to evaluate low concentration RI

  PTEP 2017 (2017) 11, 113H01
  PTEP 2018 (2018) 9, 091H01
  arXiv: 2006.09664

- Screened at multiple sites

  - ICP-MS: Kamioka

  - HPGe: Canfranc, Boulby and Kamioka

- Worked with production companies and achieved the required purity
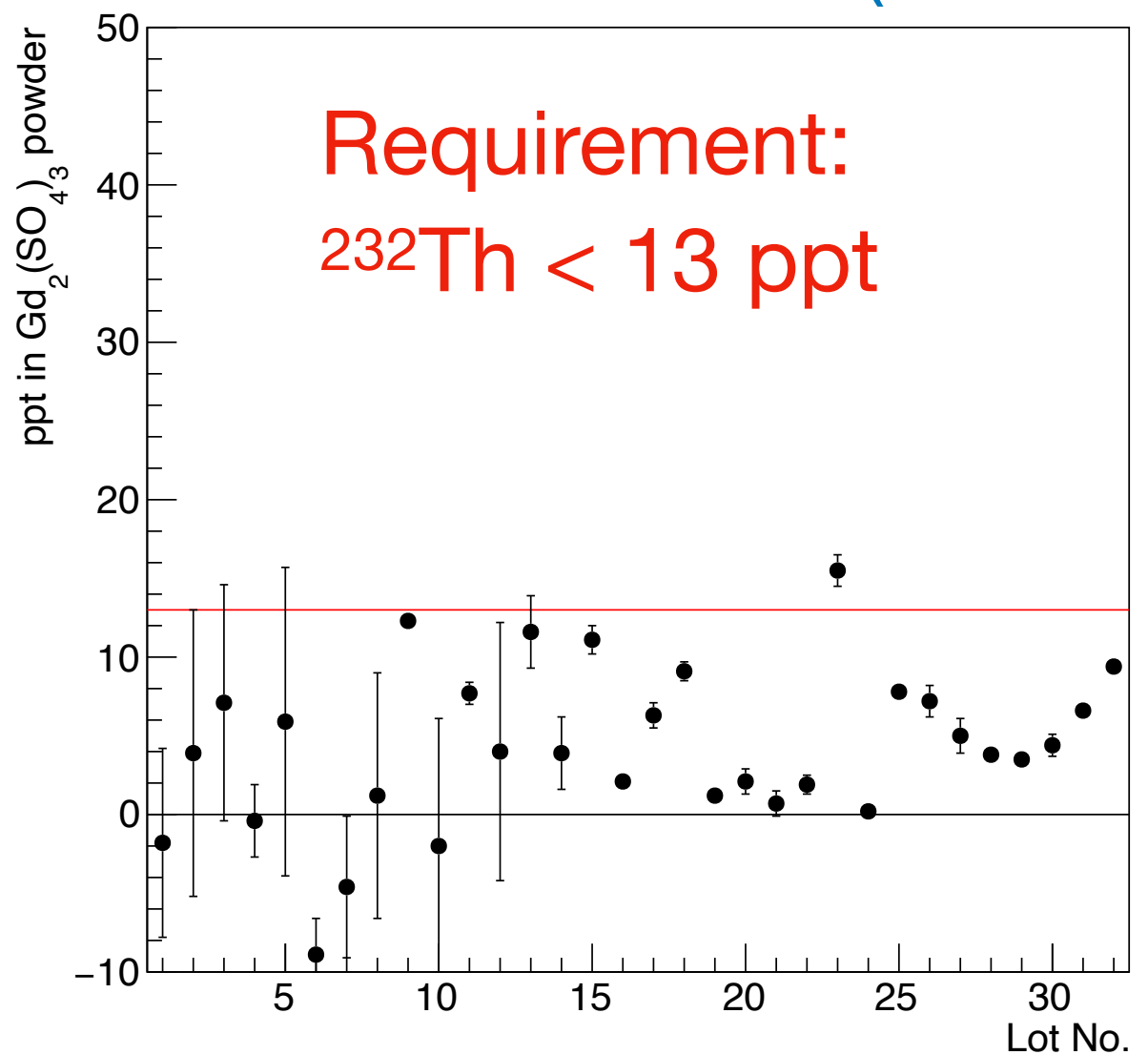
Radioactive impurities for $Gd_2(SO_4)_3$ powder [mBq/kg]

Chain	Isotope	SK-Gd requirements	
		For solar	For DSNB
^{238}U	^{238}U	—	< 5
	^{226}Ra	< 0.5	—
^{232}Th	^{228}Ra	< 0.05	—
	^{228}Th	< 0.05	—
^{235}U	^{235}U	< 30	—
	$^{227}Ac/^{227}Th$	< 30	—

U contamination (ICP-MS)

Requirement:
^{238}U < 400 ppt

Th contamination (ICP-MS)

Requirement:
^{232}Th < 13 ppt
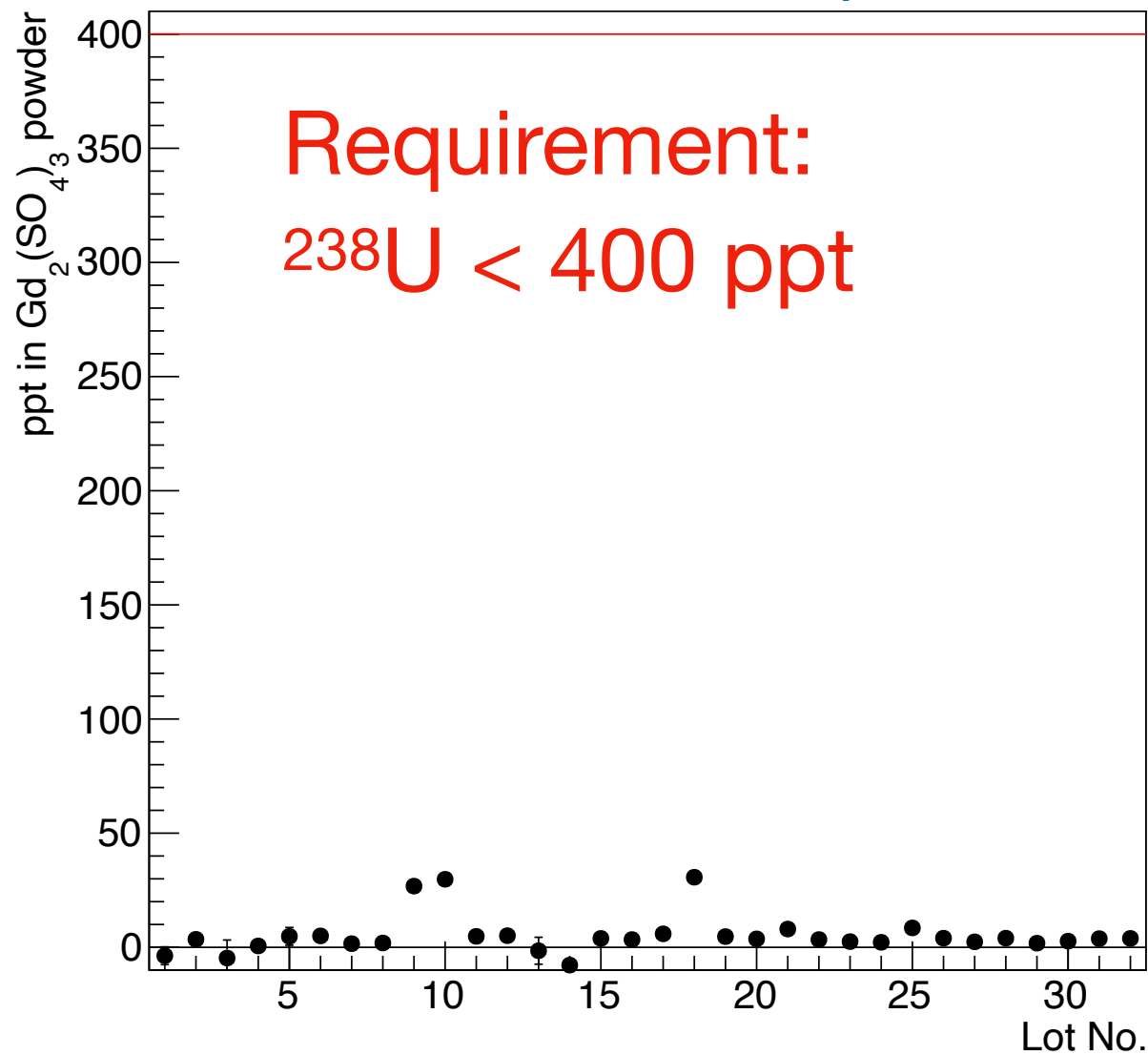
R&D Challenges (water purification)

- Challenge: remove impurities *without* removing Gd

- Two systems developed and tested with a 200 m³ tank (EGADS)

  - "Band-pass" system with nano-filter

  - Special resin-based system

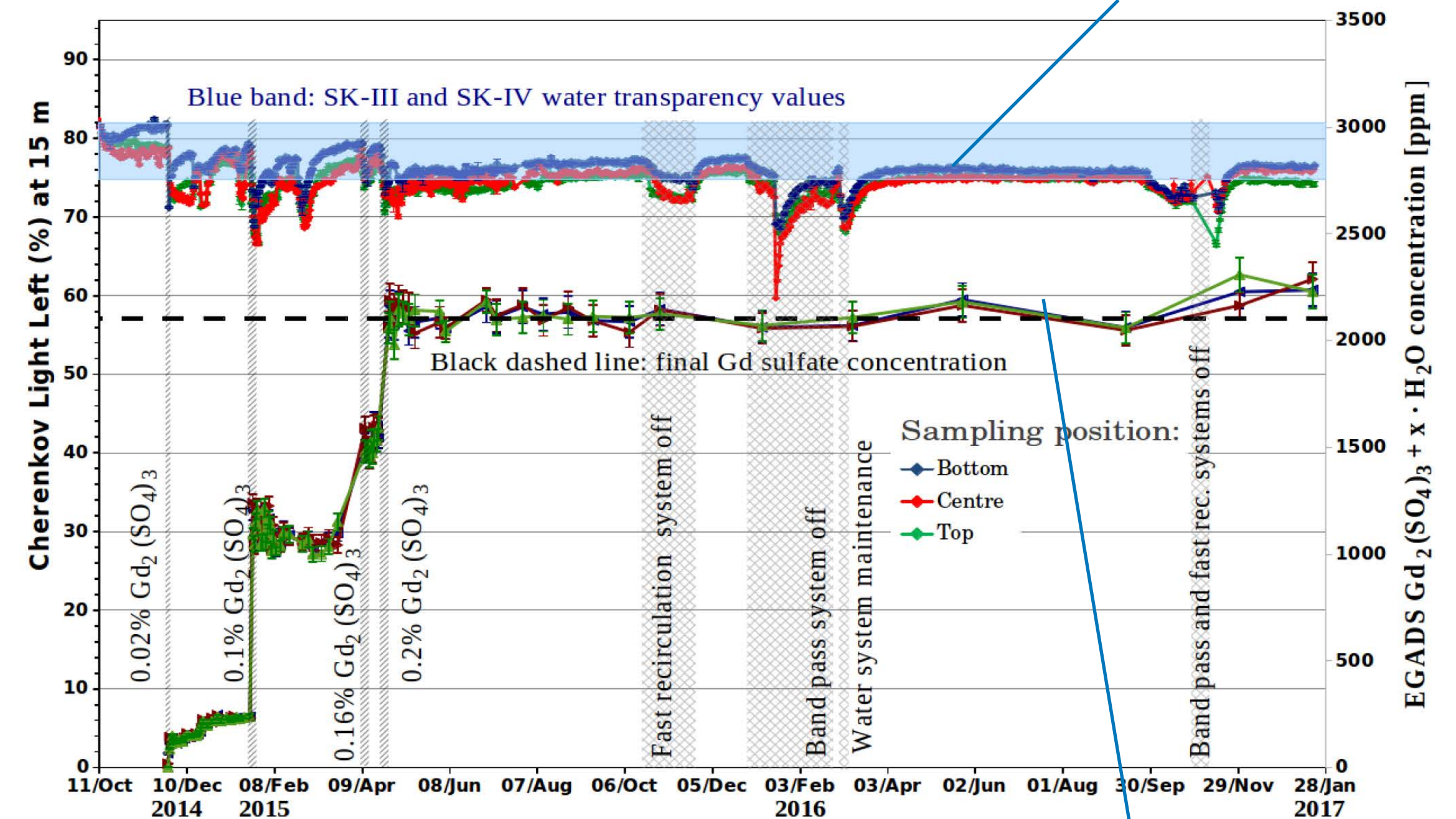 Both successfully kept water transparency at the current SK level without losing Gd

  Nucl.Instrum.Meth.A 959 (2020) 163549

- Constructed a dedicated Gd-dissolving and Gd-water purification system for Super-Kamiokande
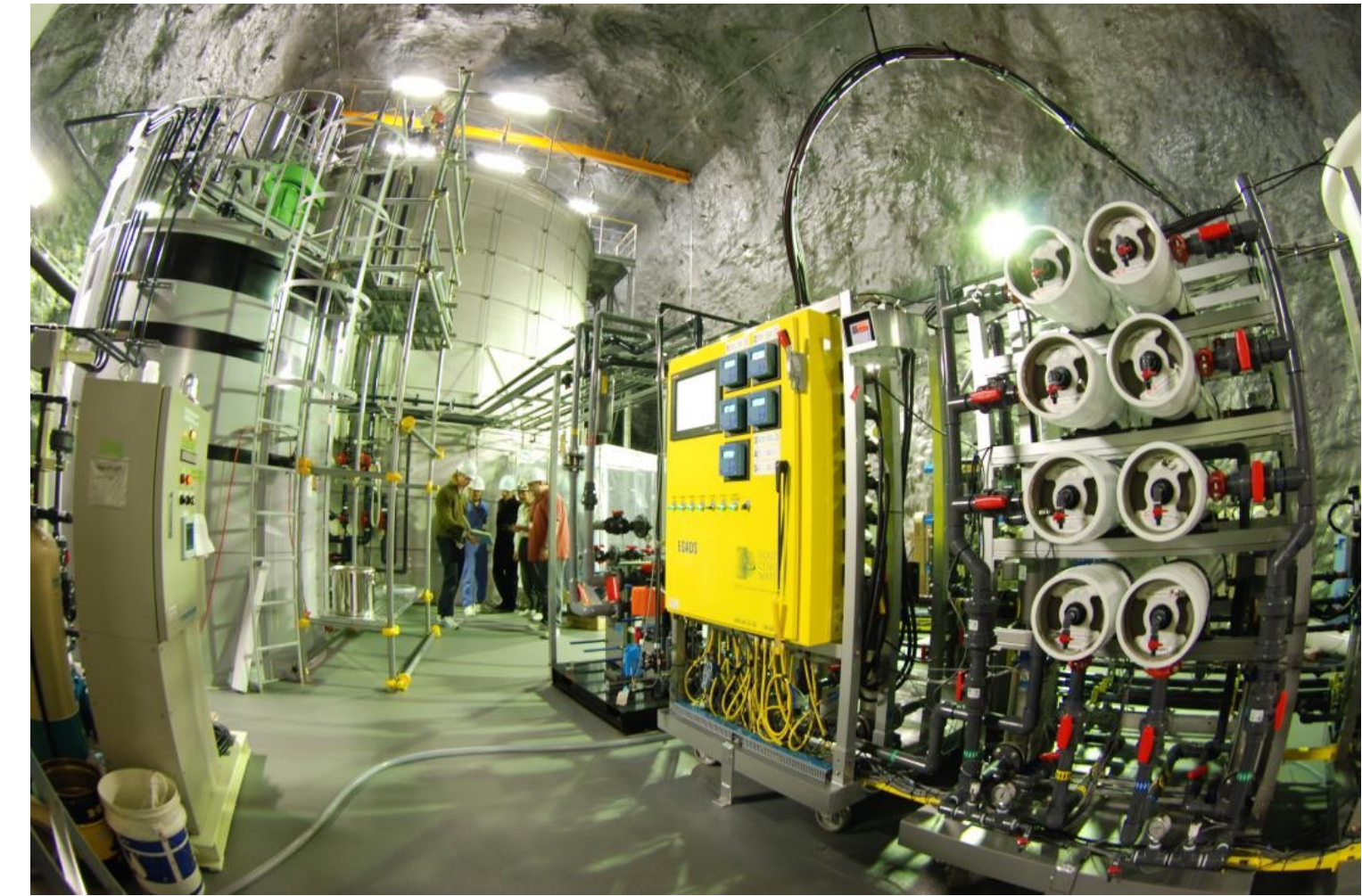
## 200 m³ tank (EGADS)

Water transparency

Gd concentration

SK detector preparation

- Major refurbishment work 2018-2019:

  - Stopped water leak: < 1/200 of before (~1 m³/d)

  - Many other improvements and cleaning

- SK-V operation (2019-):

  - The new Gd-water purification system tested with the real SK detector

    - Successfully kept water transparency at a level similar to previous phases

  - Water flow tuning: Suppressed convection and expanded low-background region
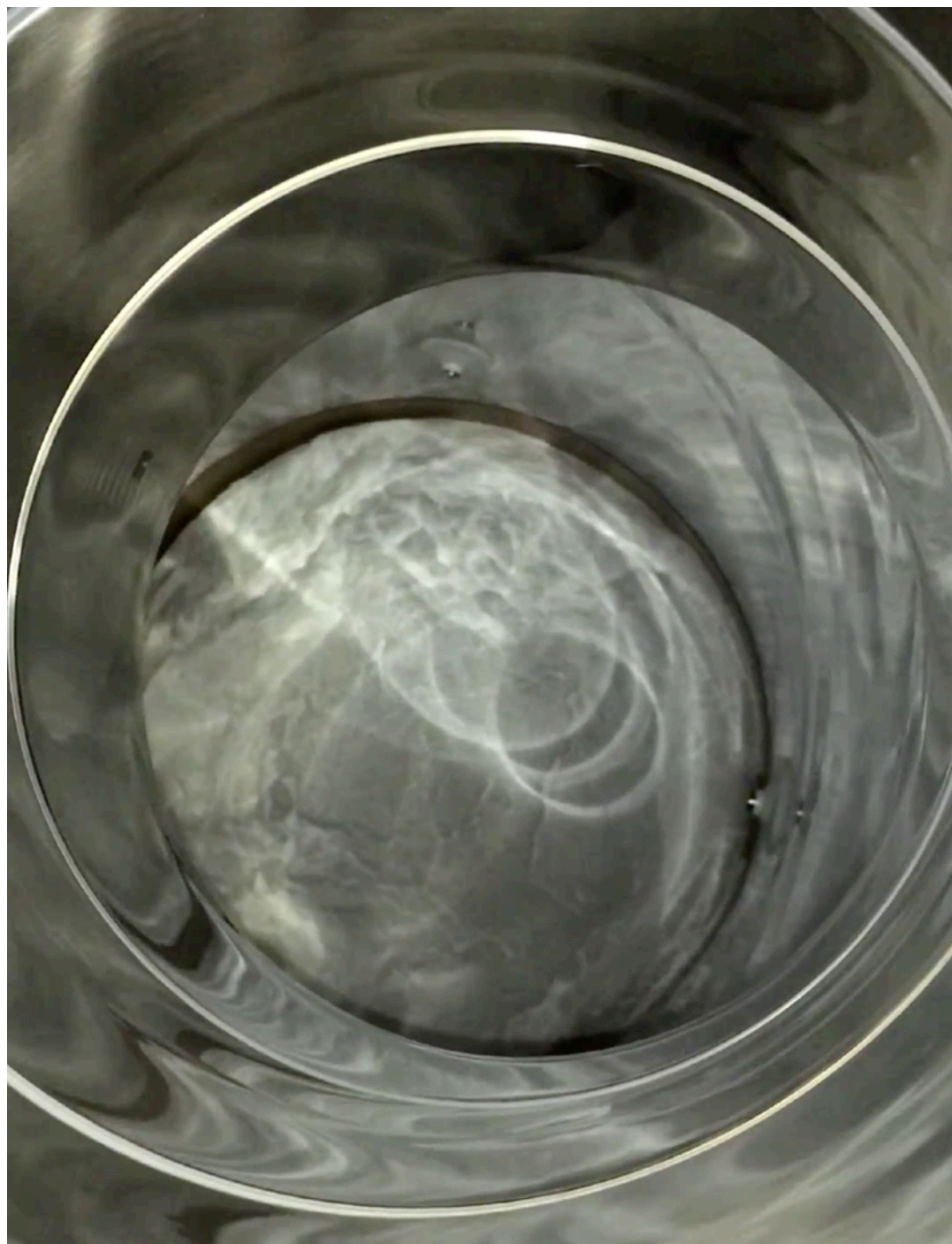
Event rate at 3.5-4.0 MeV

SK-4

SK-5
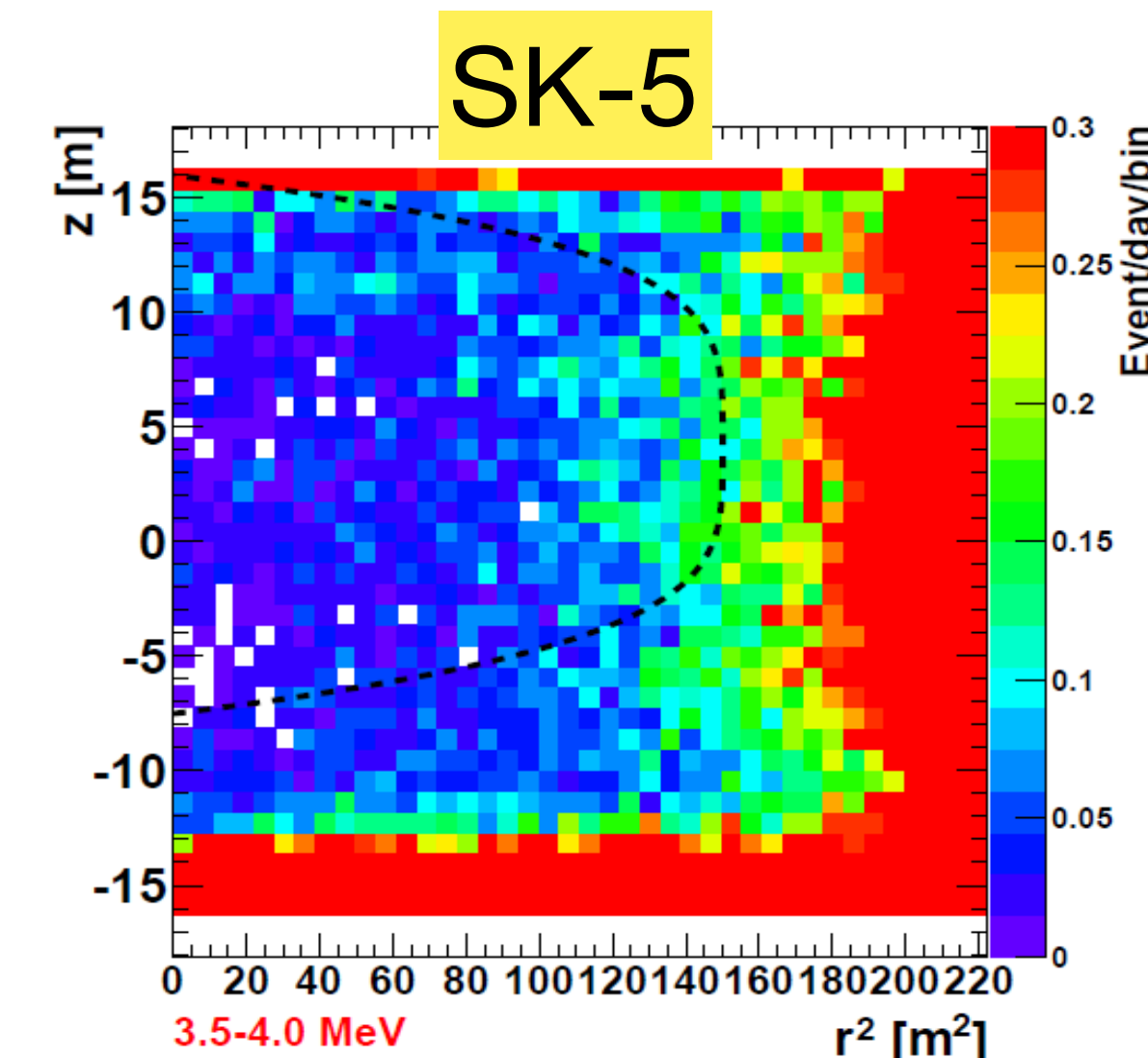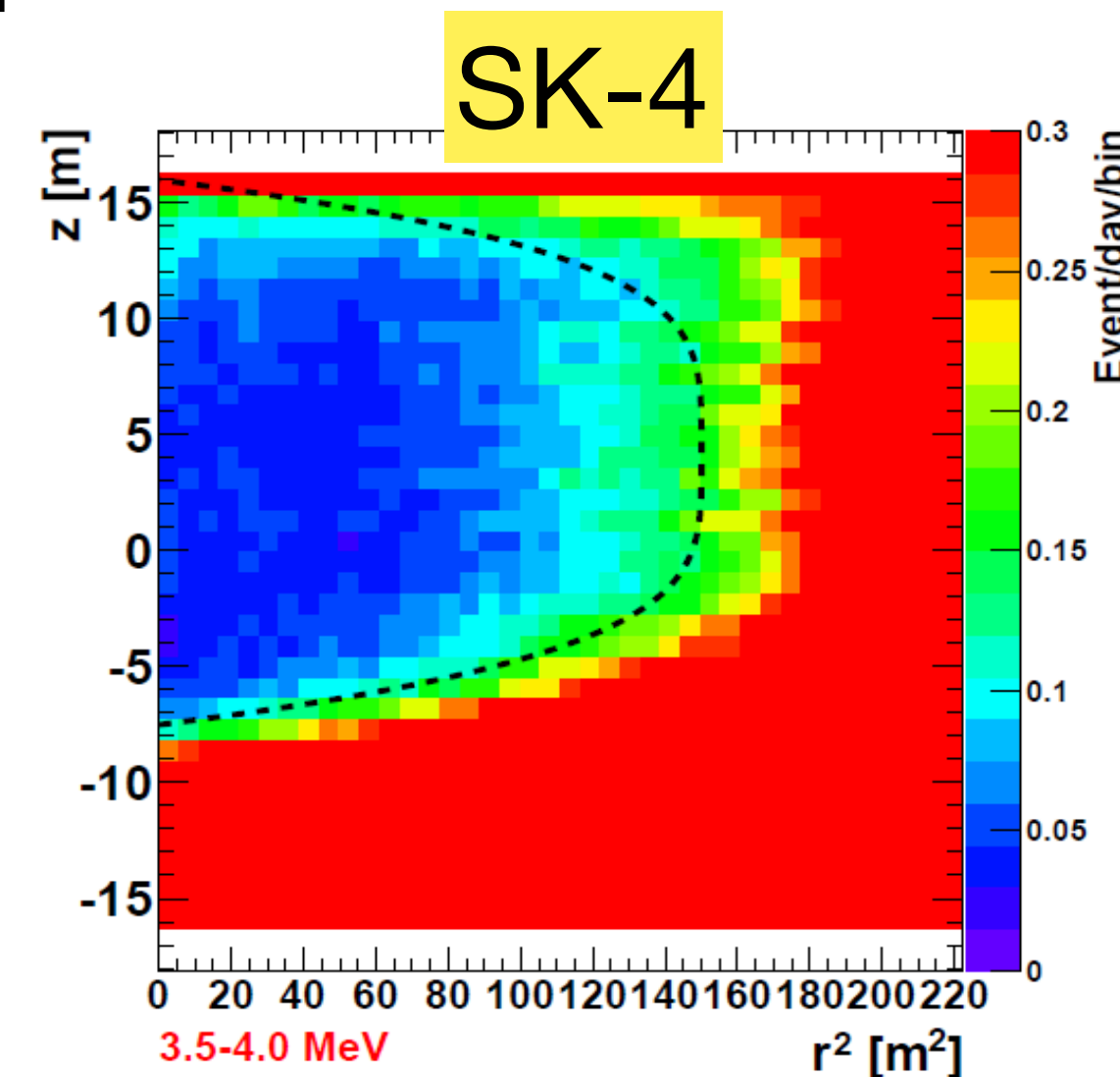
Ready, Set, …

- 14 tons of $Gd_2(SO_4)_3$ ($8H_2O$) powder for initial loading produced and screened

- The new water system is ready to process Gd-loaded water

Gd dissolving

- Commissioning of the new Gd dissolving system just started!

- Gd loading to Super-K will start *VERY* soon!

Recent results from Super-Kamiokande

New results at Neutrino 2020

- **Search for Diffuse Supernova Neutrino Backgrounds**

- **Solar neutrino oscillation measurements**

- **Atmospheric neutrino oscillation measurements**

- Multi-messenger astronomy:

  - Gravitational-wave event follow-up
    [Poster #161: M. Lamoureux]

  - Gamma-ray bust follow-up
    [Poster #85: M. Harada]

- Search for supernova bursts
  [Poster #136: M. Mori]

- Search for neutron-antineutron oscillation
  [Poster #43: L. Wan]

Recent publications (2019-)

- Phys. Rev. D 101, 052011 (2020), "Search for proton decay into three charged leptons in 0.37 megaton-years exposure of the Super-Kamiokande"

- Astrophys. J. Lett. 887, L6 (2019), "Search for Astronomical Neutrinos from Blazar TXS0506+056 in Super-Kamiokande"

- Astrophys. J. 885, 2 (2019), "Sensitivity of Super-Kamiokande with Gadolinium to Low Energy Antineutrinos from Pre-supernova Emission"

- Phys. Rev. D 99, 032005 (2019), "Measurement of the neutrino-oxygen neutral-current quasielastic cross section using atmospheric neutrinos at Super-Kamiokande"

- Prog. Theor. Exp. Phys. 2019, 053F01, "Atmospheric Neutrino Oscillation Analysis With Improved Event Reconstruction in Super-Kamiokande IV"

Supernova Neutrinos

Diffuse Supernova Neutrino Backgrounds
a.k.a Supernova Relic Neutrinos (SRN)

- Supernova burst neutrinos:

  - Rich physics observables once detected

  - No detection since 1987A. Most recent search in [Poster #136: M. Mori]

- **Diffuse Supernova Neutrino Backgrounds (DSNB)**:

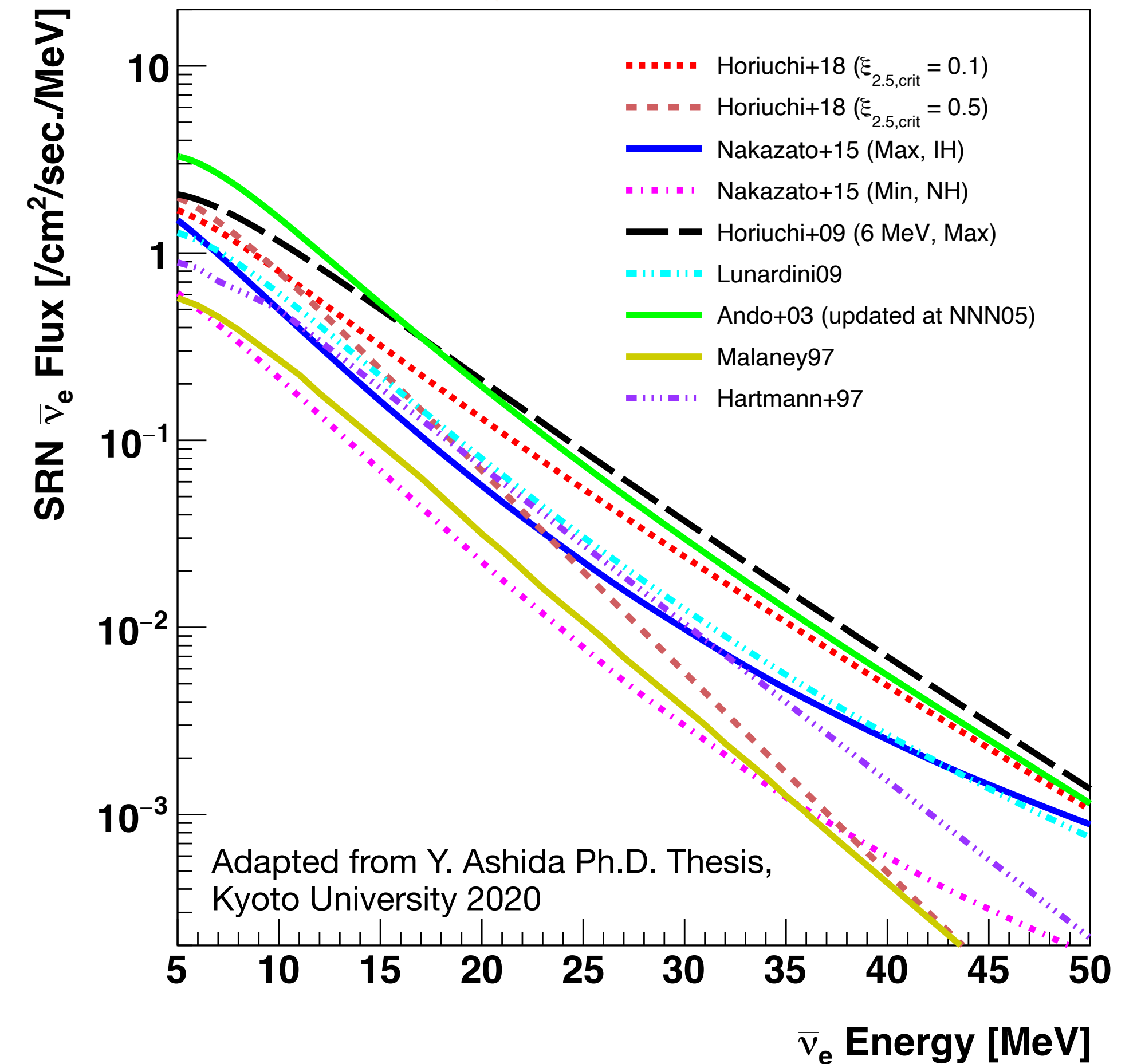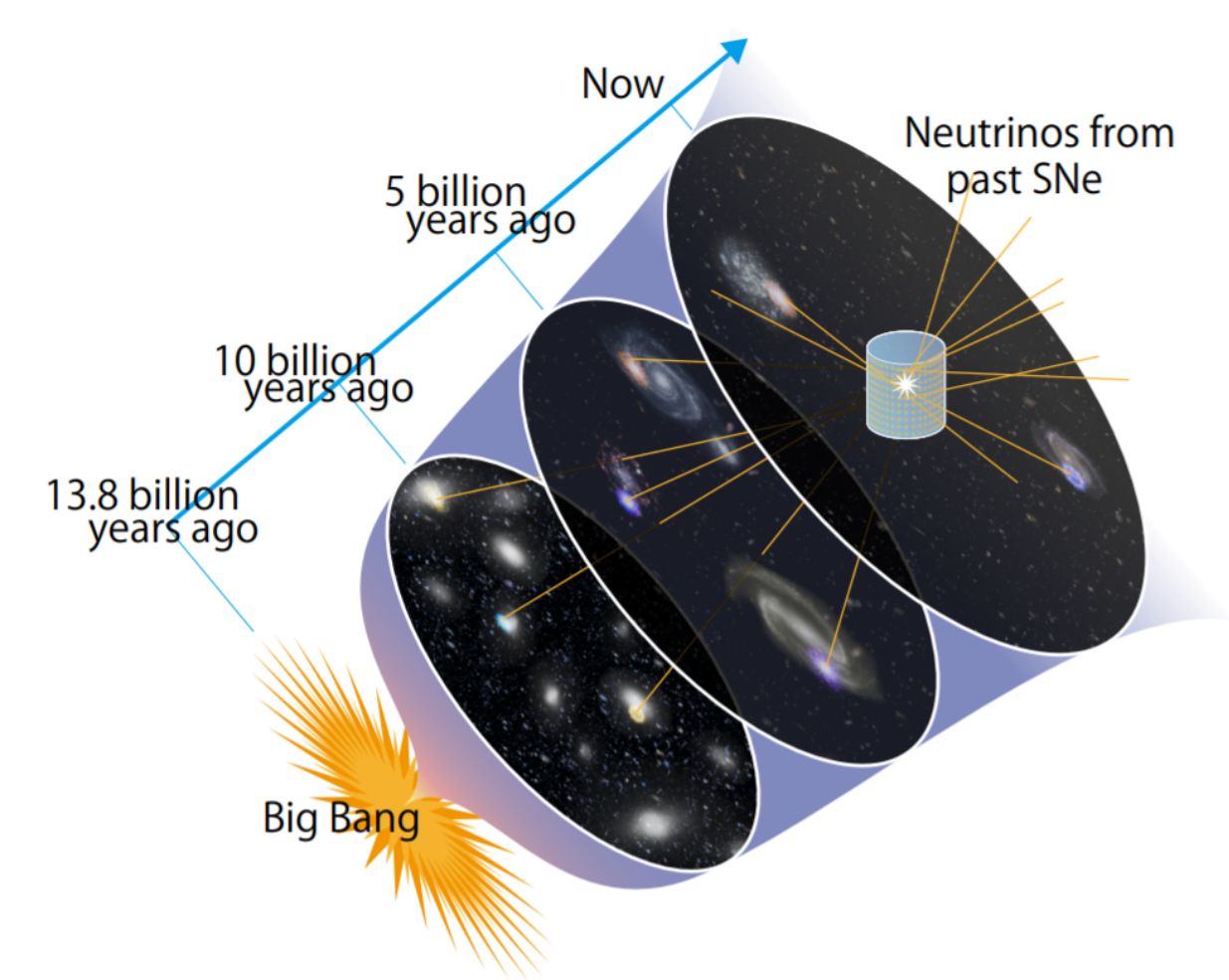 - Neutrinos produced from all the SN bursts and diffused in the current universe.

    ~ a few SN explosions every second

    $O(10^{18})$ SNe so far in this universe

  - Can study history of SN bursts with neutrinos

$$\frac{dF_\nu}{dE_\nu} = c \int_0^{z_{\max}} R_{SN}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

  z_{max} ~ 1 for SK energy range

  - Many astrophysics and particle physics implications:

    - Contribution of failed supernova

    - Neutrino oscillation effect in dense medium

    - Galaxy evolution

    - Supernova burst mechanism

Now
Neutrinos from past SNe
5 billion years ago
10 billion years ago
13.8 billion years ago
Big Bang

SRN $\bar{\nu}_e$ Flux [/cm²/sec./MeV]

$\bar{\nu}_e$ Energy [MeV]

- - - - Horiuchi+18 ($\xi_{2.5,crit}$ = 0.1)
- - - - Horiuchi+18 ($\xi_{2.5,crit}$ = 0.5)
——— Nakazato+15 (Max, IH)
-·-·- Nakazato+15 (Min, NH)
- - - Horiuchi+09 (6 MeV, Max)
-·-·- Lunardini09
——— Ando+03 (updated at NNN05)
——— Malaney97
-··-·· Hartmann+97

Adapted from Y. Ashida Ph.D. Thesis, Kyoto University 2020

DSNB: Signal and Backgrounds

Rare event search: a few interactions / year / SK

- Primary signal: Inverse Beta Decay ($\bar{\nu}_e + p \to e^+ + n$)
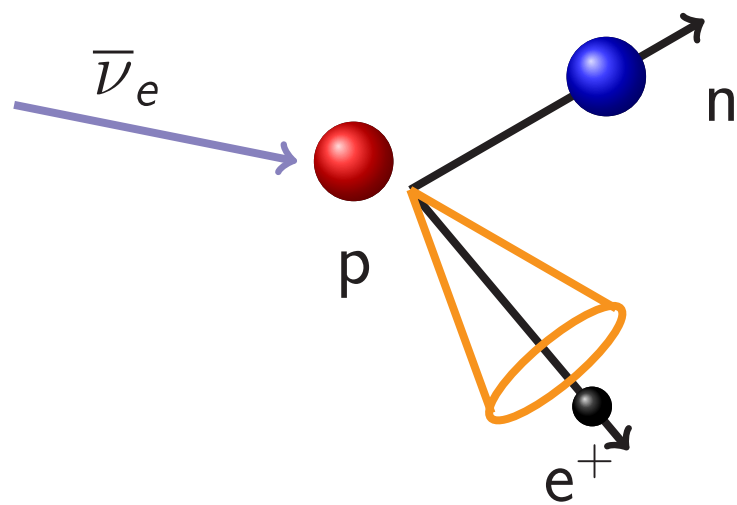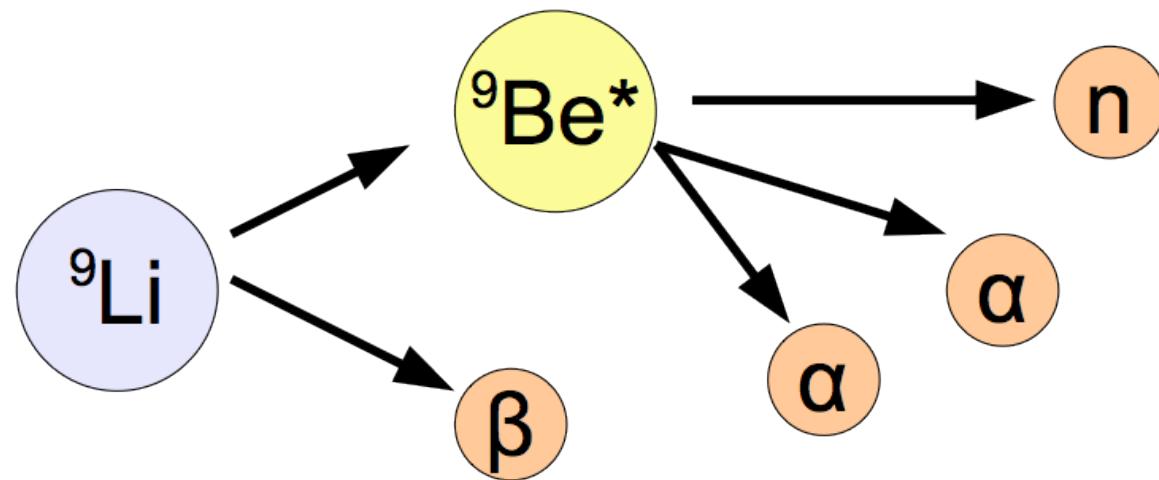

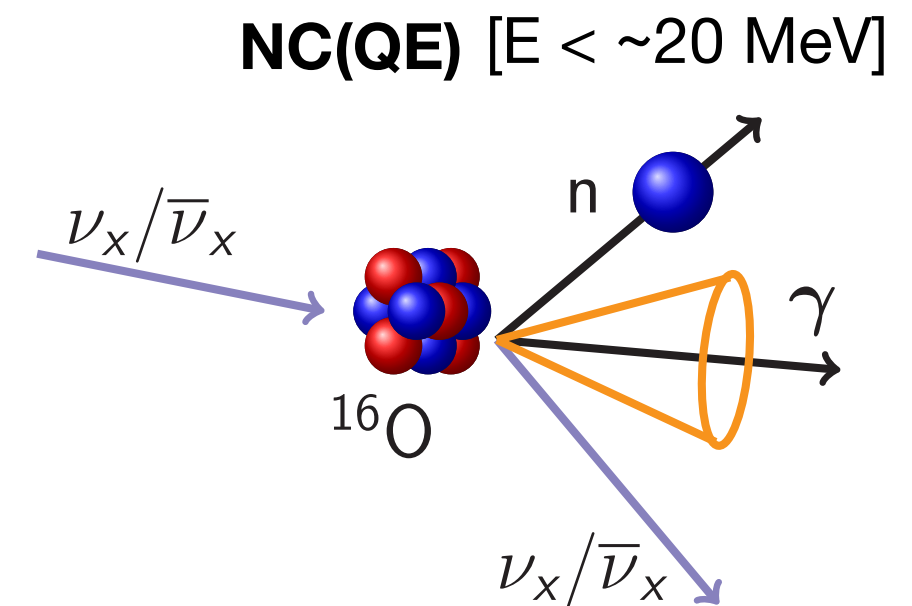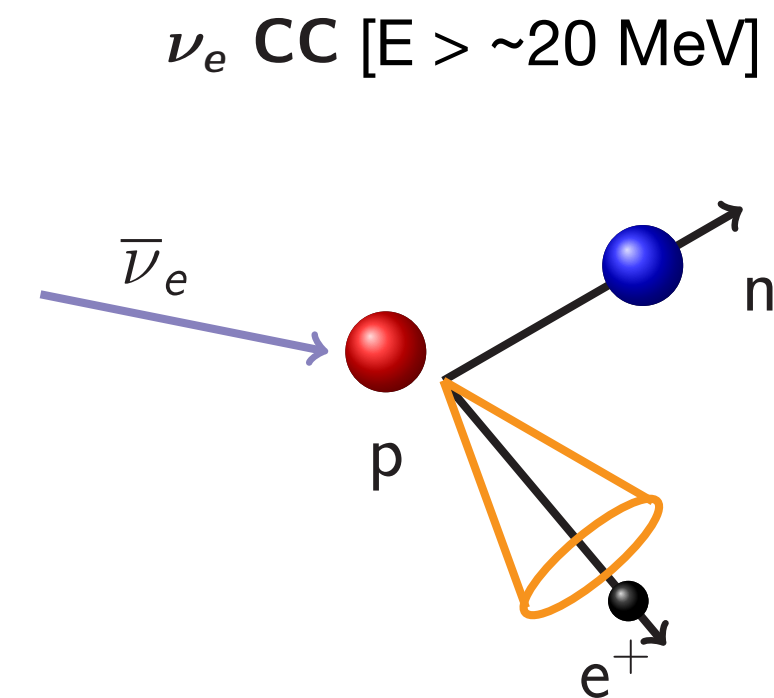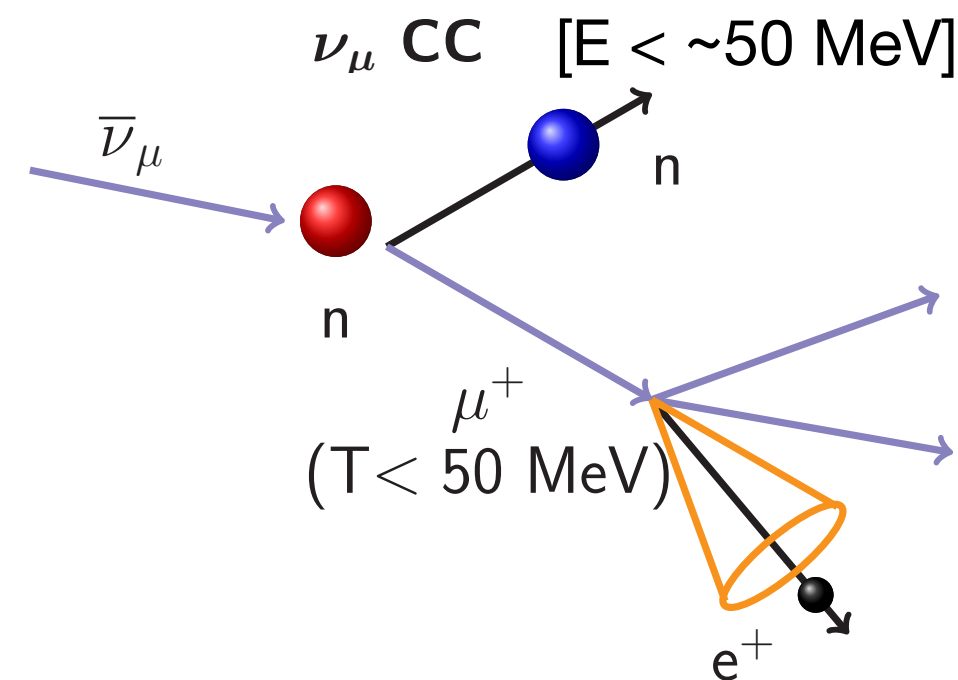Detecting both position and neutron is the key to reduce backgrounds

- Backgrounds that mimic e+ + n pair:

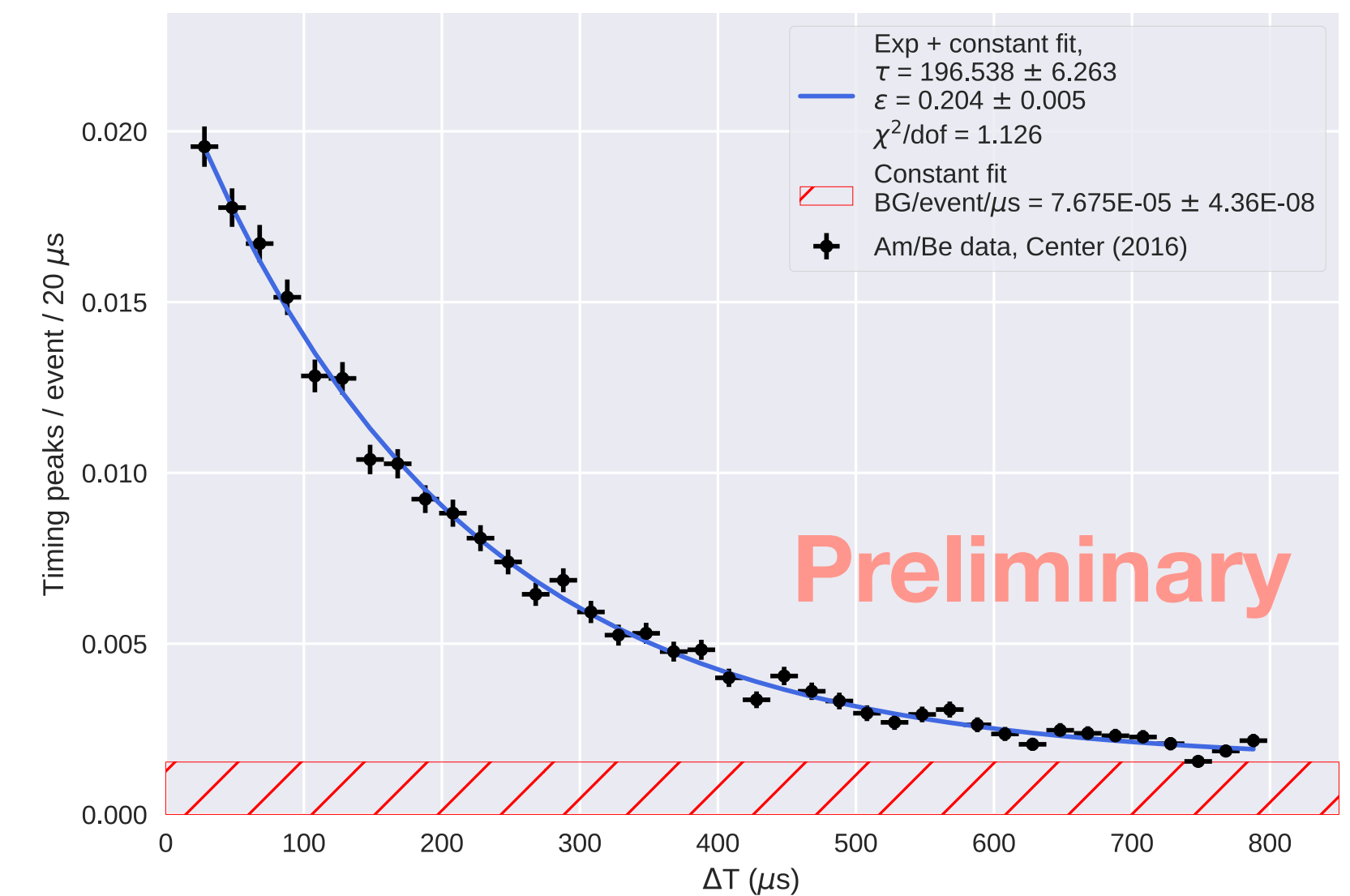 - **⁹Li (from cosmic μ spallation)**
    [E < ~15 MeV]

  - **Atmospheric neutrinos** [Poster #175: S. Sakai]

  ν_μ **CC** [E < ~50 MeV] ν_e **CC** [E > ~20 MeV]   **NC(QE)** [E < ~20 MeV]

- **Accidental coincidence (mostly spallation products + fake-neutrons)** [E < ~15 MeV]
- **Reactor neutrinos** [E < ~10 MeV]   [Poster #221: A. Goldsack]

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Analysis method

- Employed neutron tagging:

  - Neutron signal in SK (pure water): 2.2 MeV γ from n-H capture

    - Very small (typically ~ 7 PMT hits) signal

    - Buried in radioactivity from the detector

  - Developed a neutron selection algorithm based on Boosted Decision Tree

    - 20-30% signal efficiency with 0.2-3% fake-tag rate

- Two methods for testing DSNB signal

  - Spectrum fit: Fit spectrum shape assuming a DSNB model

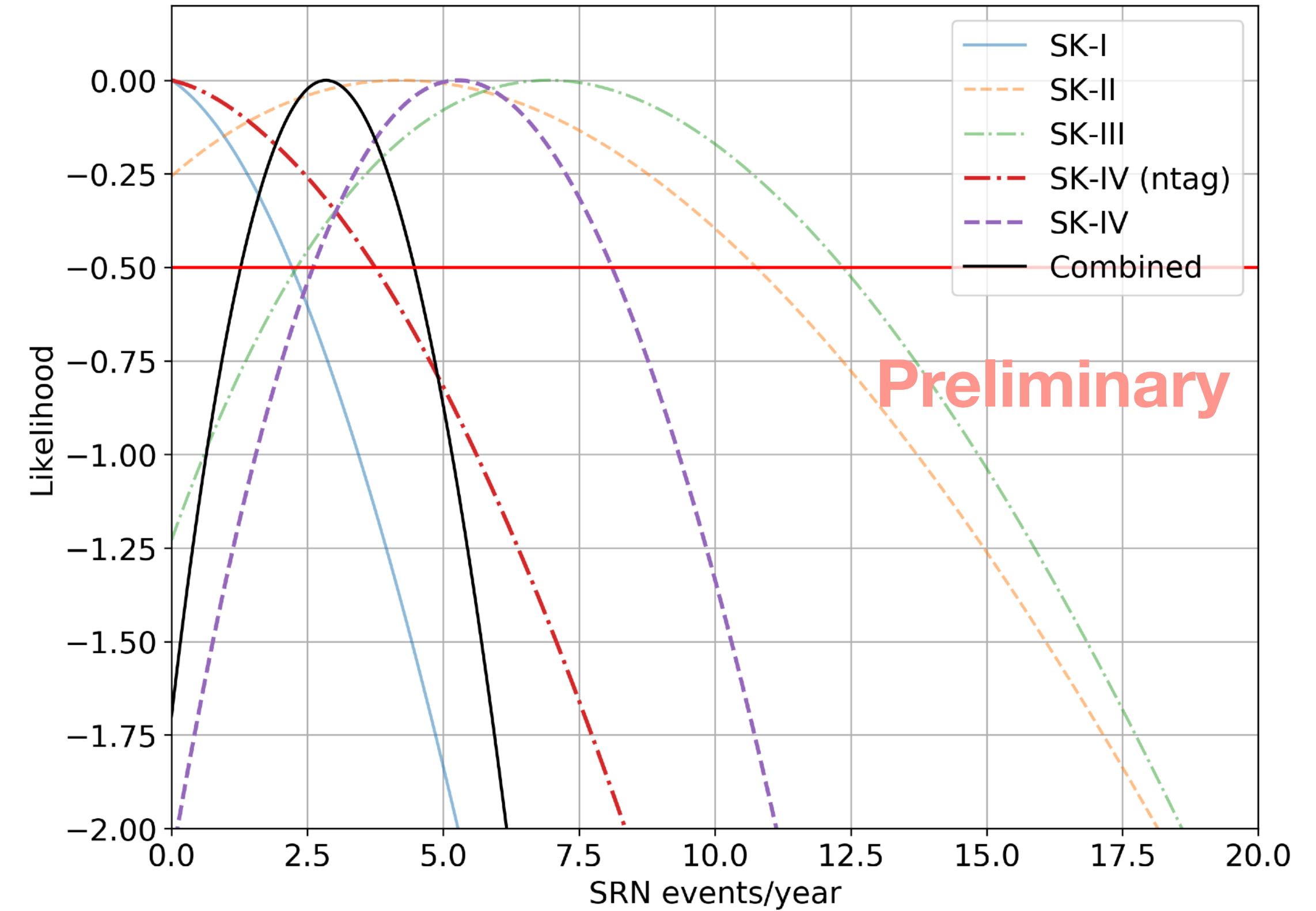 - DSNB-model independent search: Test event excess for each reconstructed energy bin

Neutron tagging performance

Overall efficiencies for our analysis

Preliminary

Exp + constant fit,
$\tau = 196.538 \pm 6.263$
$\varepsilon = 0.204 \pm 0.005$
$\chi^2/\text{dof} = 1.126$

Constant fit
BG/event/μs = 7.675E-05 ± 4.36E-08
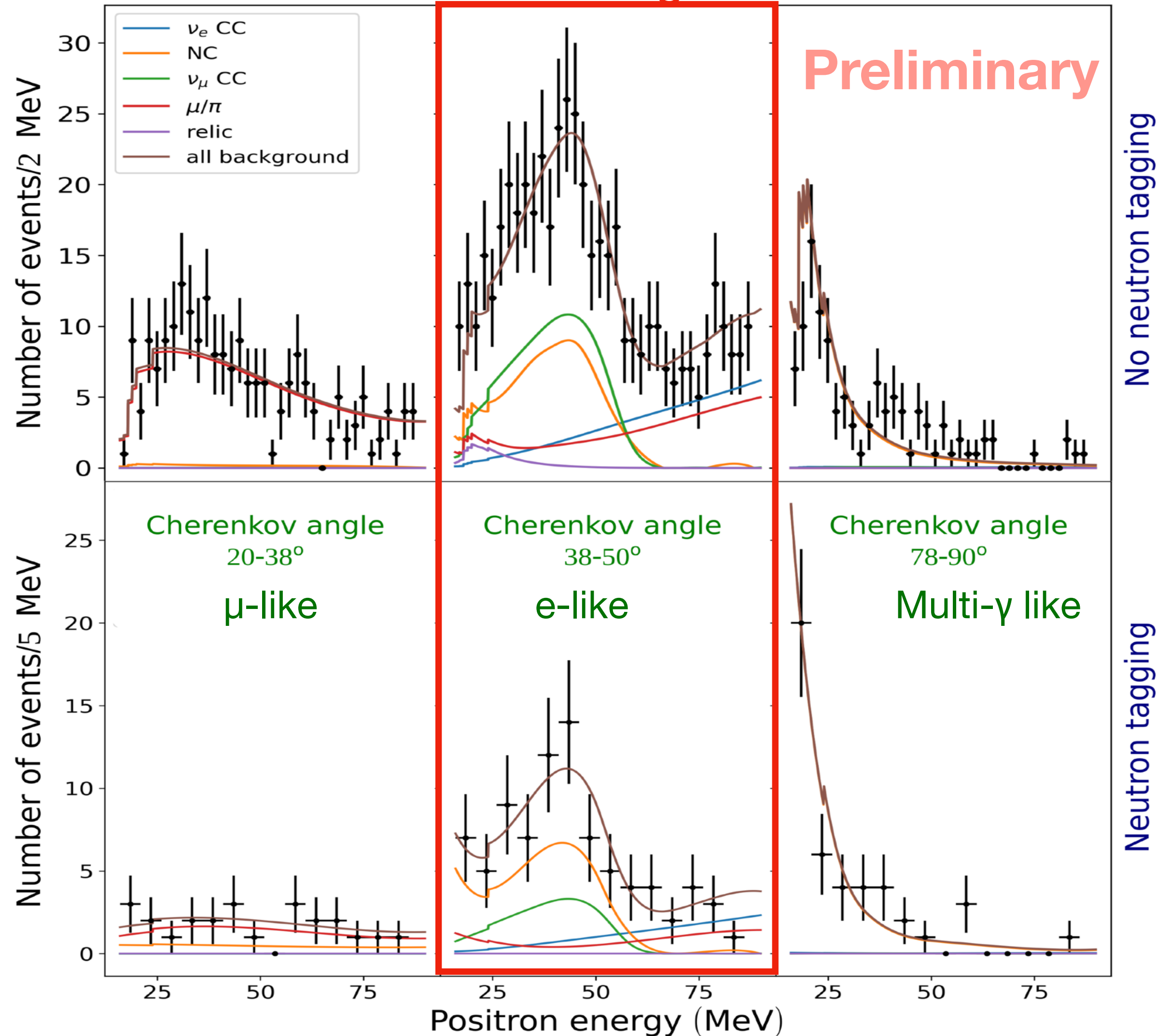
+ Am/Be data, Center (2016)

Preliminary
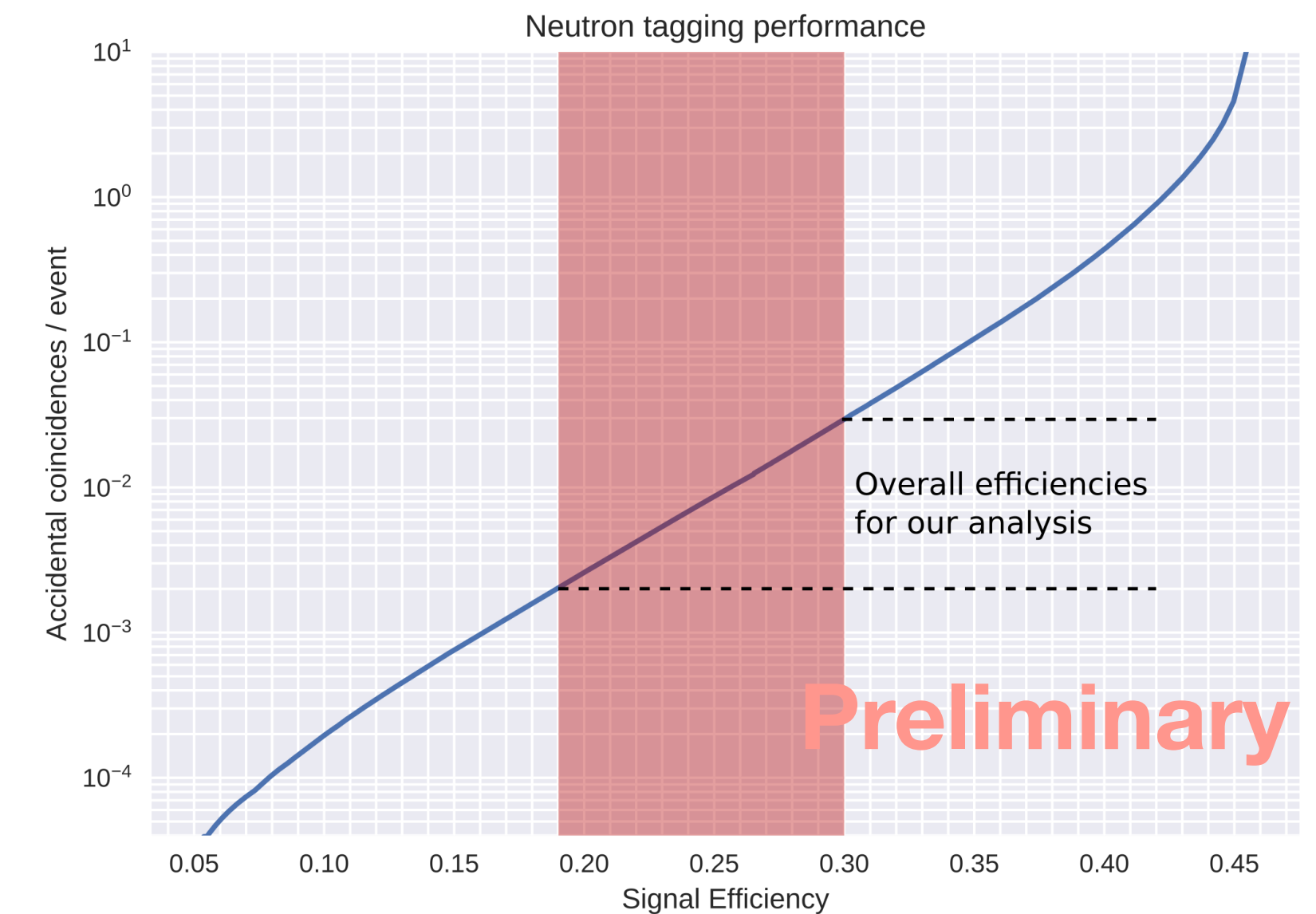
[Poster #231: S. El Hedri]

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Spectrum fit result

$E_p > 16$ MeV

SK-IV data   DSNB region   Spectrum shape from [Ando et al (NNN05)]

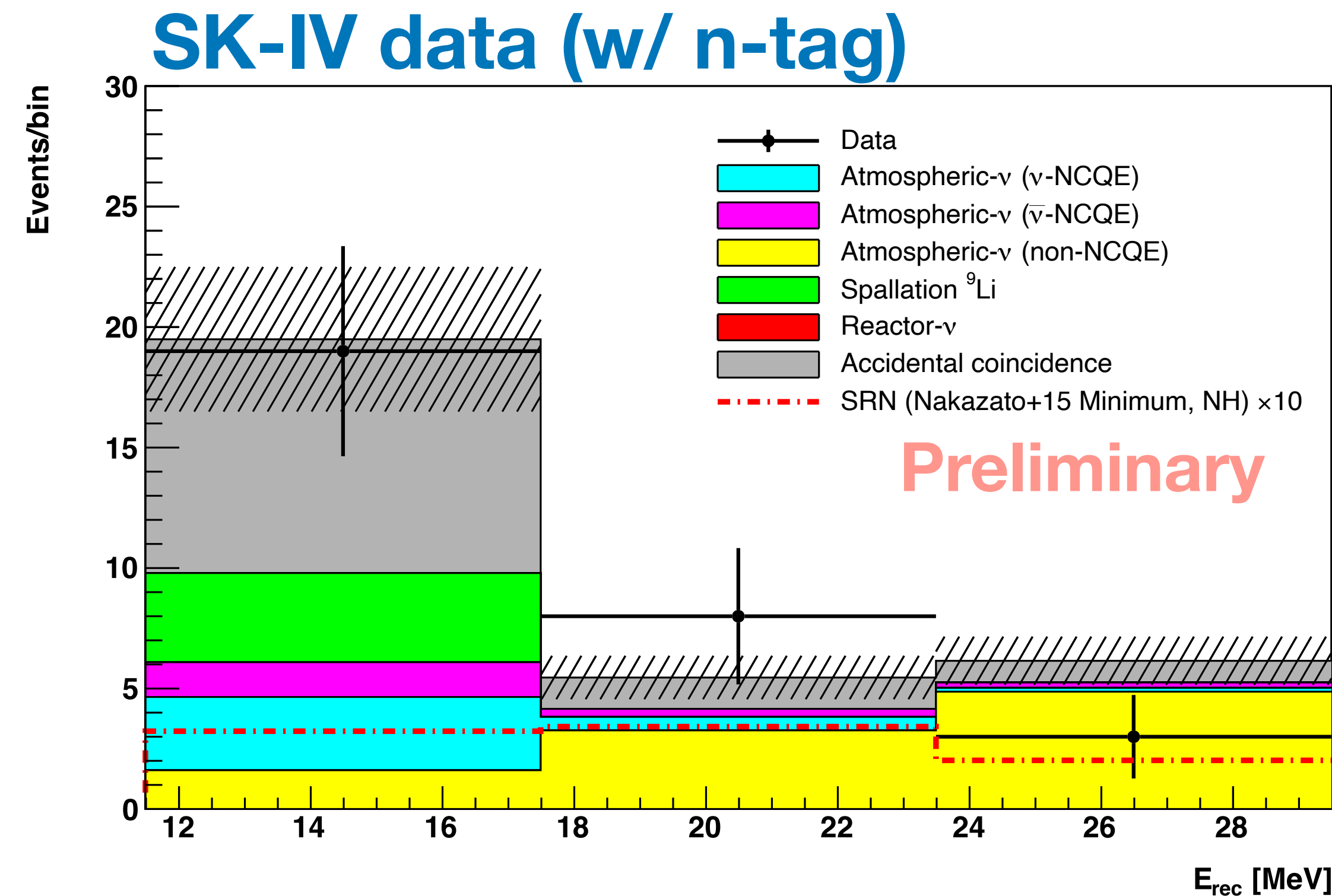**Preliminary**

Preliminary

No significant excess observed

Combined limit: **φ < 2.7 cm^{-2}/s (90% CL) for E$_p$ > 16 MeV**

Model prediction: φ = 1.7 cm^{-2}/s [Ando et al (NNN05)]

Limit within a factor two of this prediction!

DSNB-model independent search

SK-IV data (w/ n-tag)

Preliminary

Search Results & Integrated SRN Electron Antineutrino Flux [/cm²/sec.]

| E_v region [MeV]	13.3–19.3	19.3–25.3	25.3–31.3
SK-IV 2970 days (Expected)	9.48	1.35	0.82
SK-IV 2970 days (Observed)	9.08	2.22	0.35
Horiuchi+18 ($\xi_{2.5,crit} = 0.1$)	1.583	0.553	0.173
Horiuchi+18 ($\xi_{2.5,crit} = 0.5$)	1.108	0.252	0.050
Nakazato+15 (Maximum, IH)	0.798	0.236	0.081
Nakazato+15 (Minimum, NH)	0.337	0.089	0.026
Horiuchi+09 (6 MeV, Maximum)	2.534	0.887	0.314
Lunardini09	1.032	0.321	0.098
Ando+03 (updated at NNN05)	2.652	0.796	0.261
Malaney97	0.469	0.125	0.034
Hartmann+97	0.947	0.297	0.093

☐ : Models within a factor of 3

- No significant excess found

- Set one of the most stringent limits above 13.3 MeV

- Many model predictions are within several factors from the current limit

- Sensitivity limited by small statistics and backgrounds

→**Will be significantly improved with better neutron tagging in SK-Gd**

Solar Neutrinos

Solar Neutrinos

- Intense neutrinos from nuclear fusion in the Sun's core

  - Majority (99%) from pp-chain with subdominant contribution from CNO cycle

- What's left in solar neutrinos?

  - Help understanding solar interior

  - **Precision test of the MSW oscillation model**

    - Precise measurement of spectrum at the vacuum-to-matter transition region

    - Measurement of Day/Night asymmetry

- Super-K's measurement of solar neutrinos

  - Detecting recoil electrons from elastic scattering

  - Robust signal extraction using angular correlation with the Sun

  - Current threshold for analysis: $E_{kin} > 3.5$ MeV
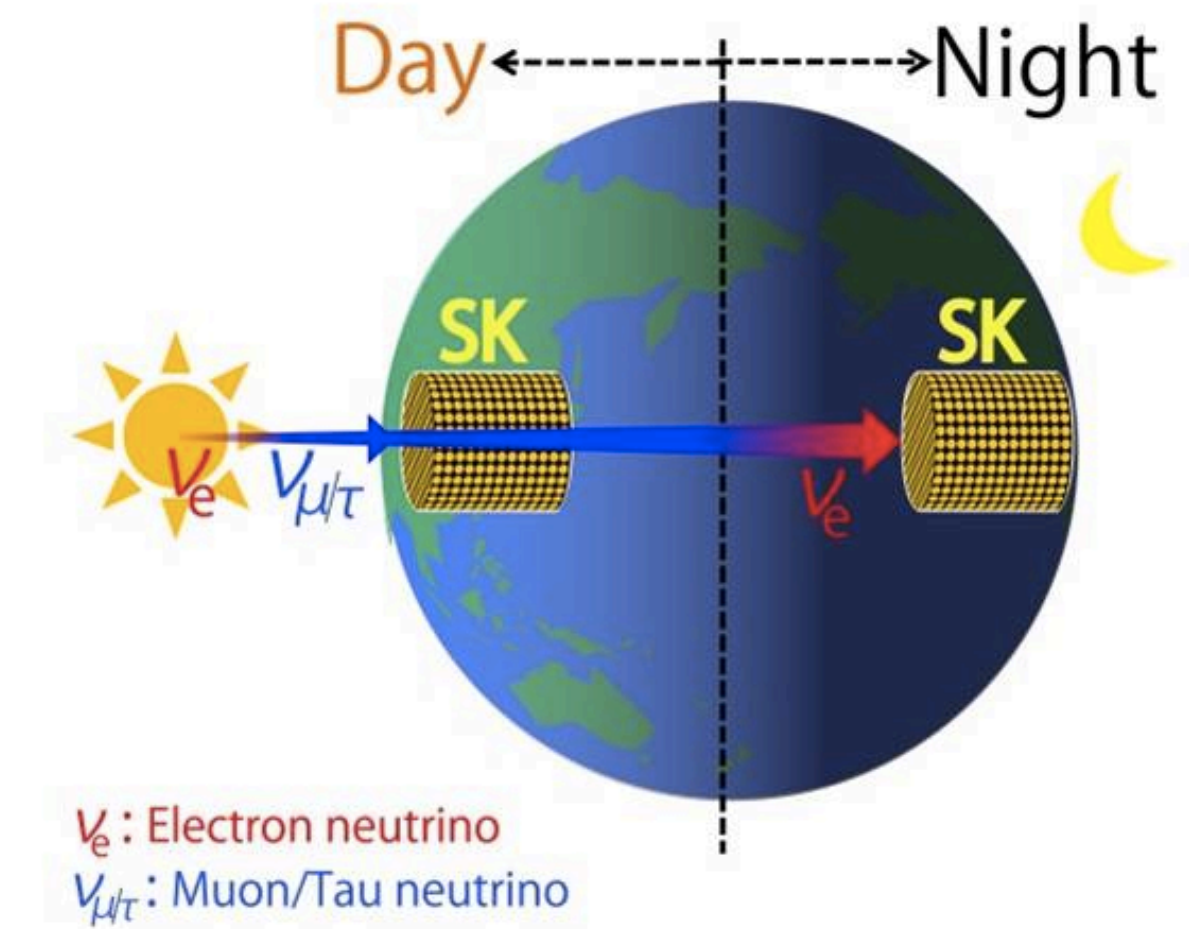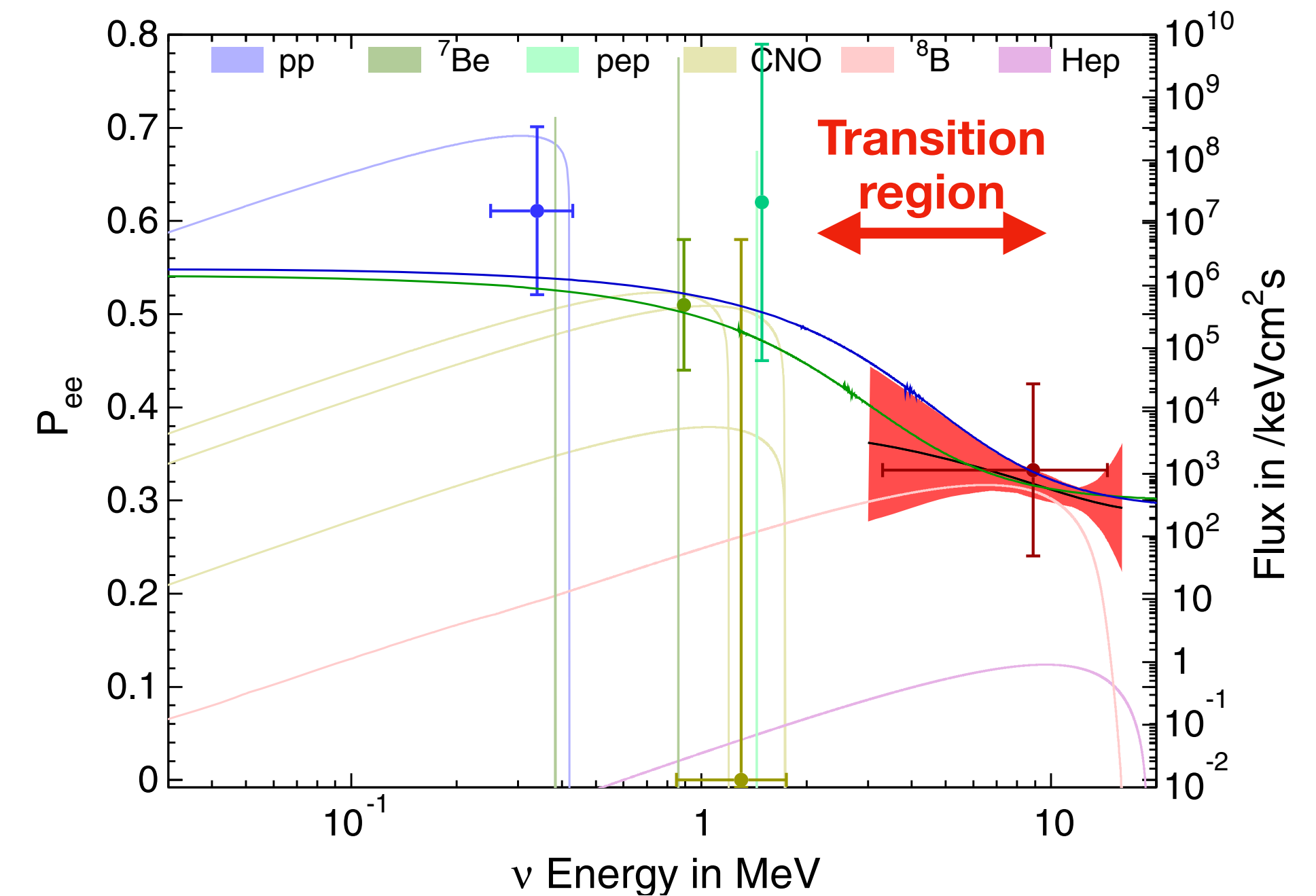
Super-K has been continuously improving analysis with more statistics

Analysis Improvements

- Detector simulation improvements [Poster #350: Y. Nakano]

  - Improved PMT hit timing simulation

  - Improved modeling of water quality non-uniformity

- Analysis improvements [Poster #350: Y. Nakano]

  - Correction for PMT gain drift (introduced in 2017)

  - Improved correction for non-uniform energy response

    E-scale non-uniformity (MC) 1.7% → 0.5%

- Improved spallation cut [Poster #166: S. Locke]

  - 12% more signal efficiency while keeping spallation rejection efficiency at a similar level (~90%)
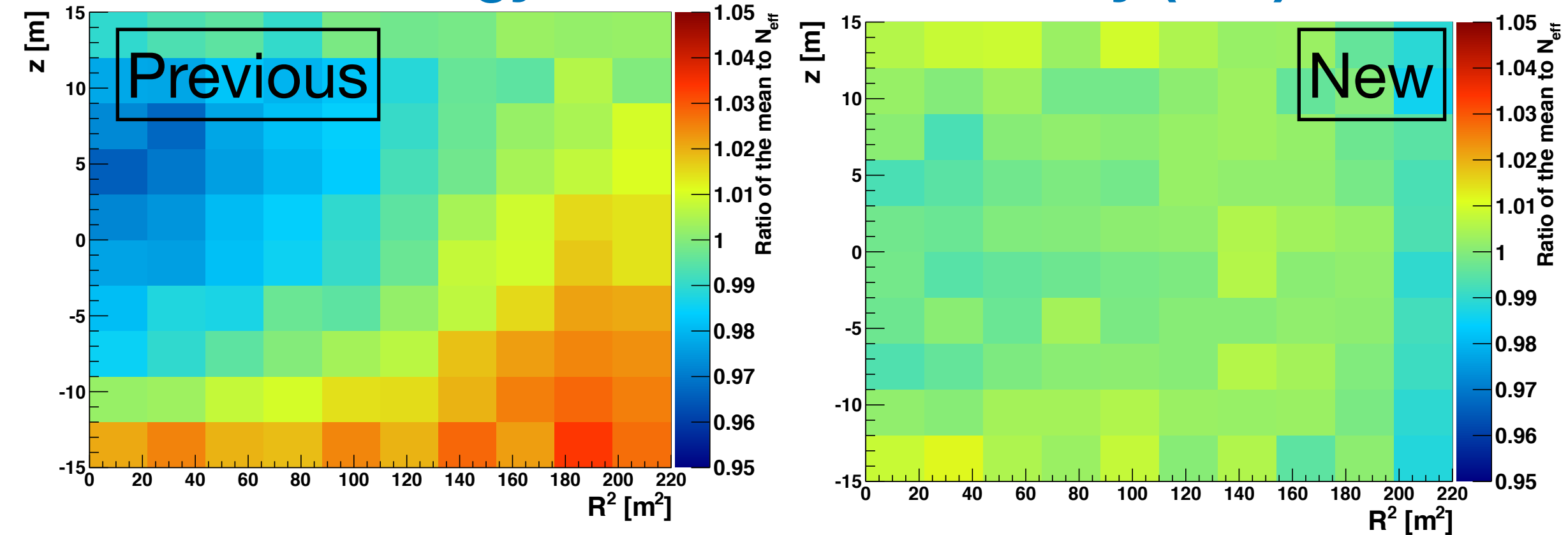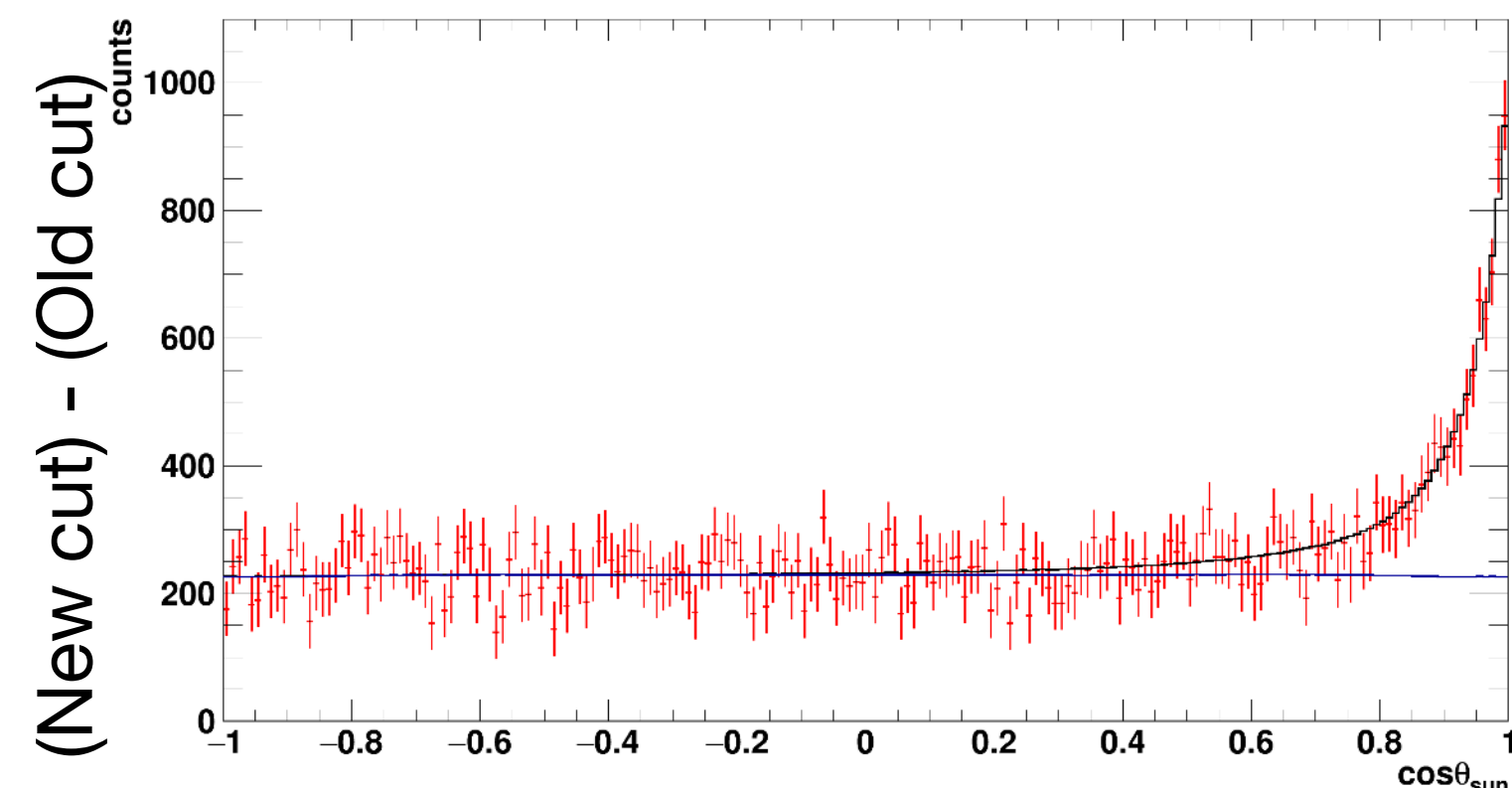
    Gained ~1 year worth statistics

Energy scale stability (decay-e from cosmic μ)
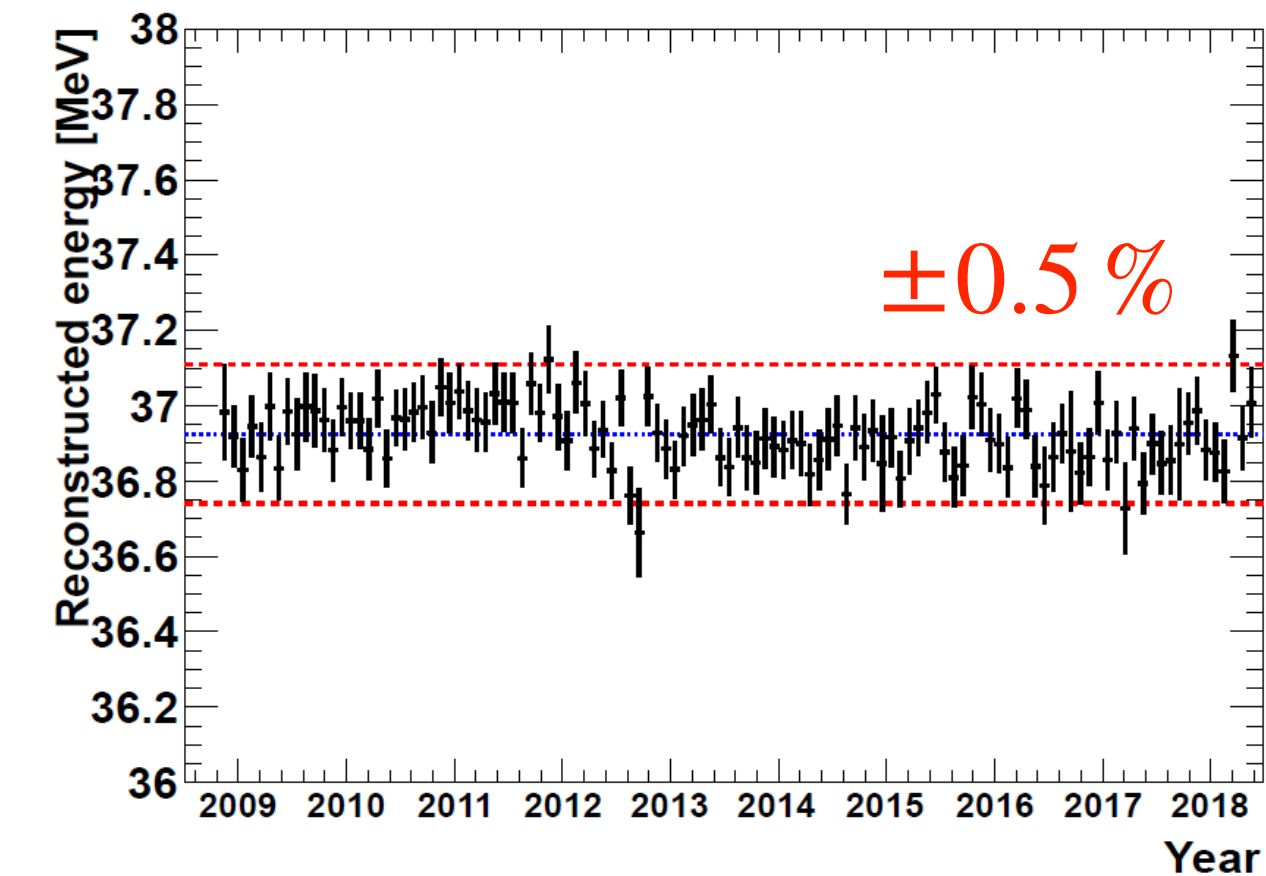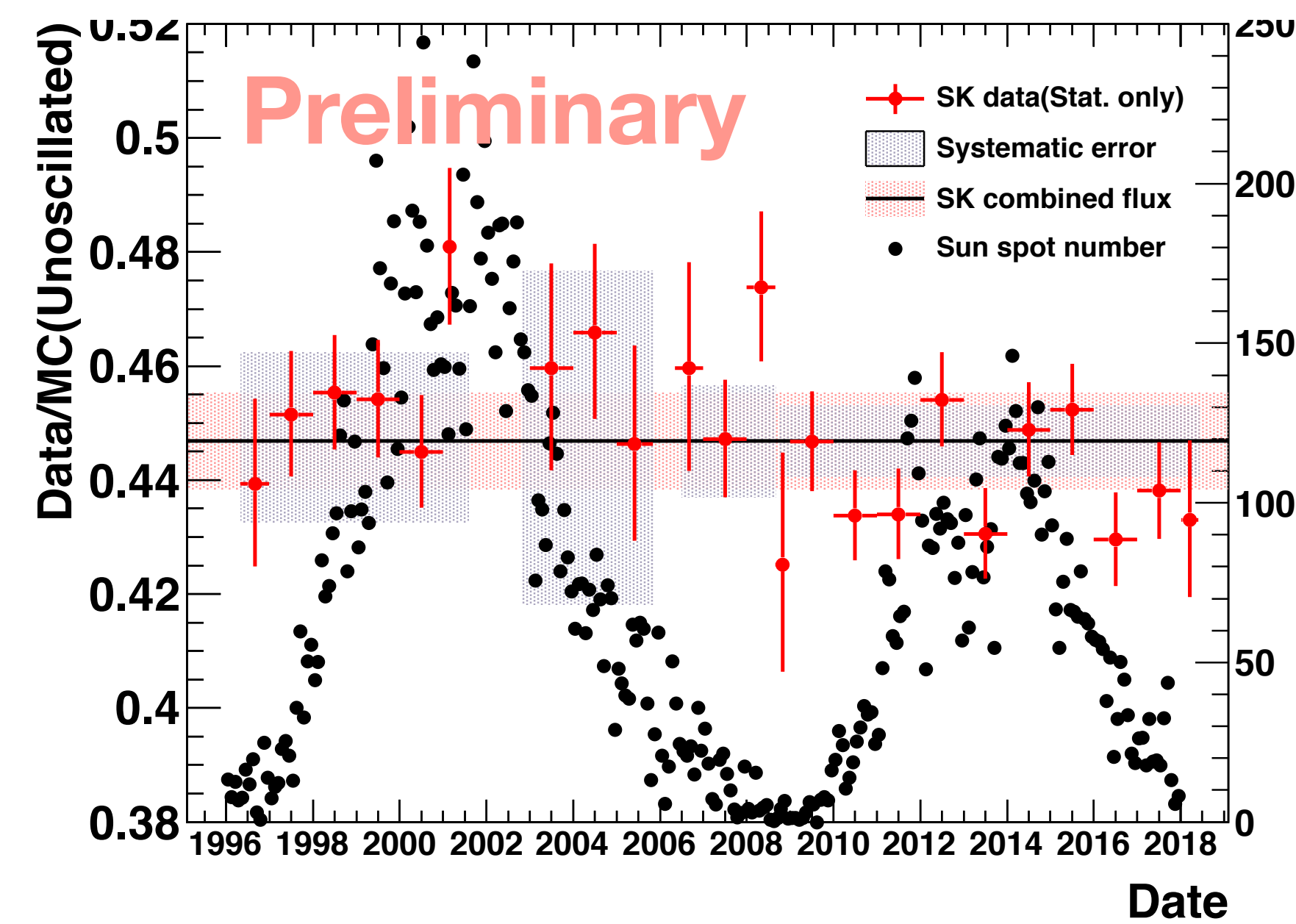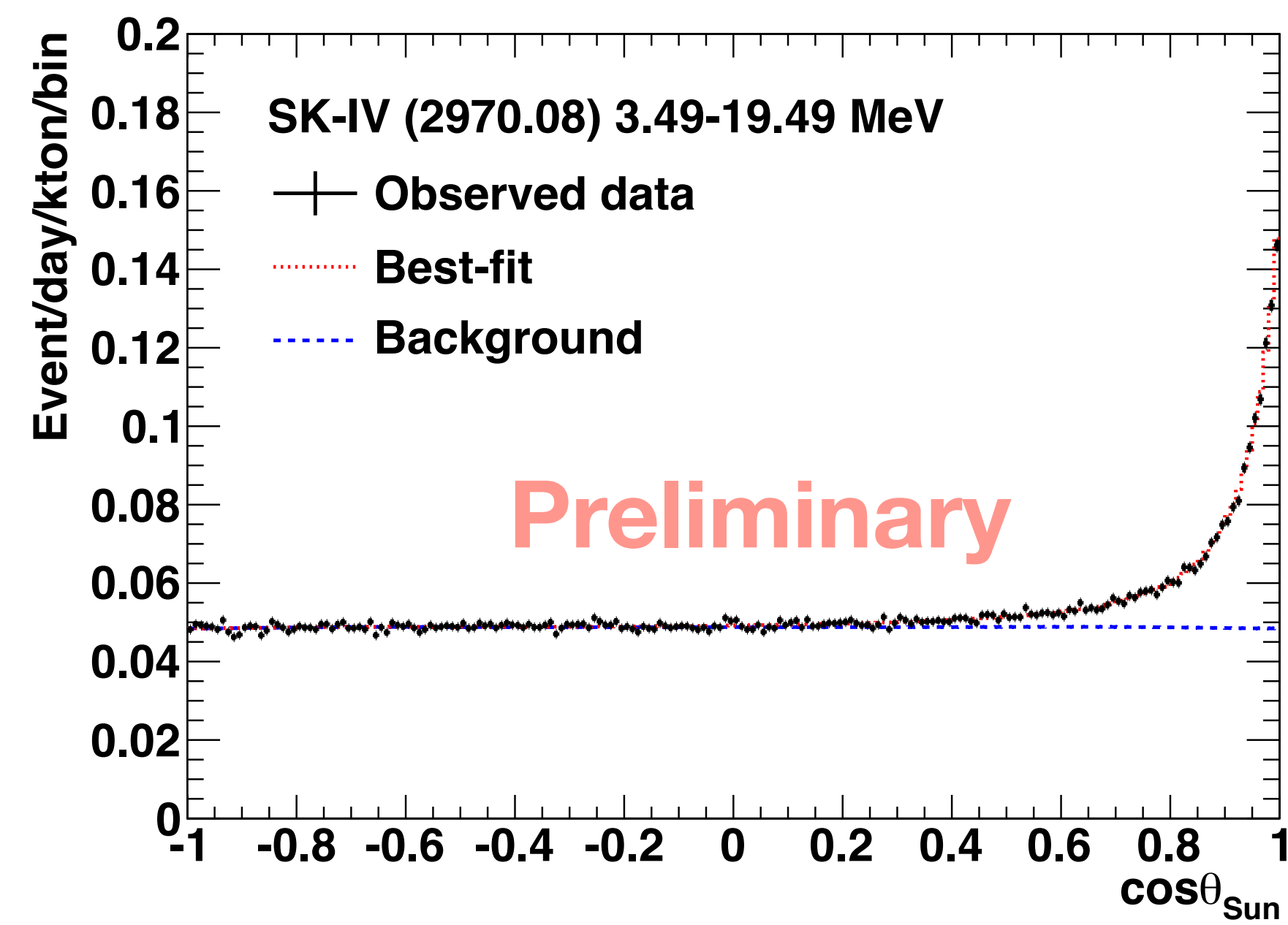

Energy scale non-uniformity (MC)

Additional events w/ new spallation cut
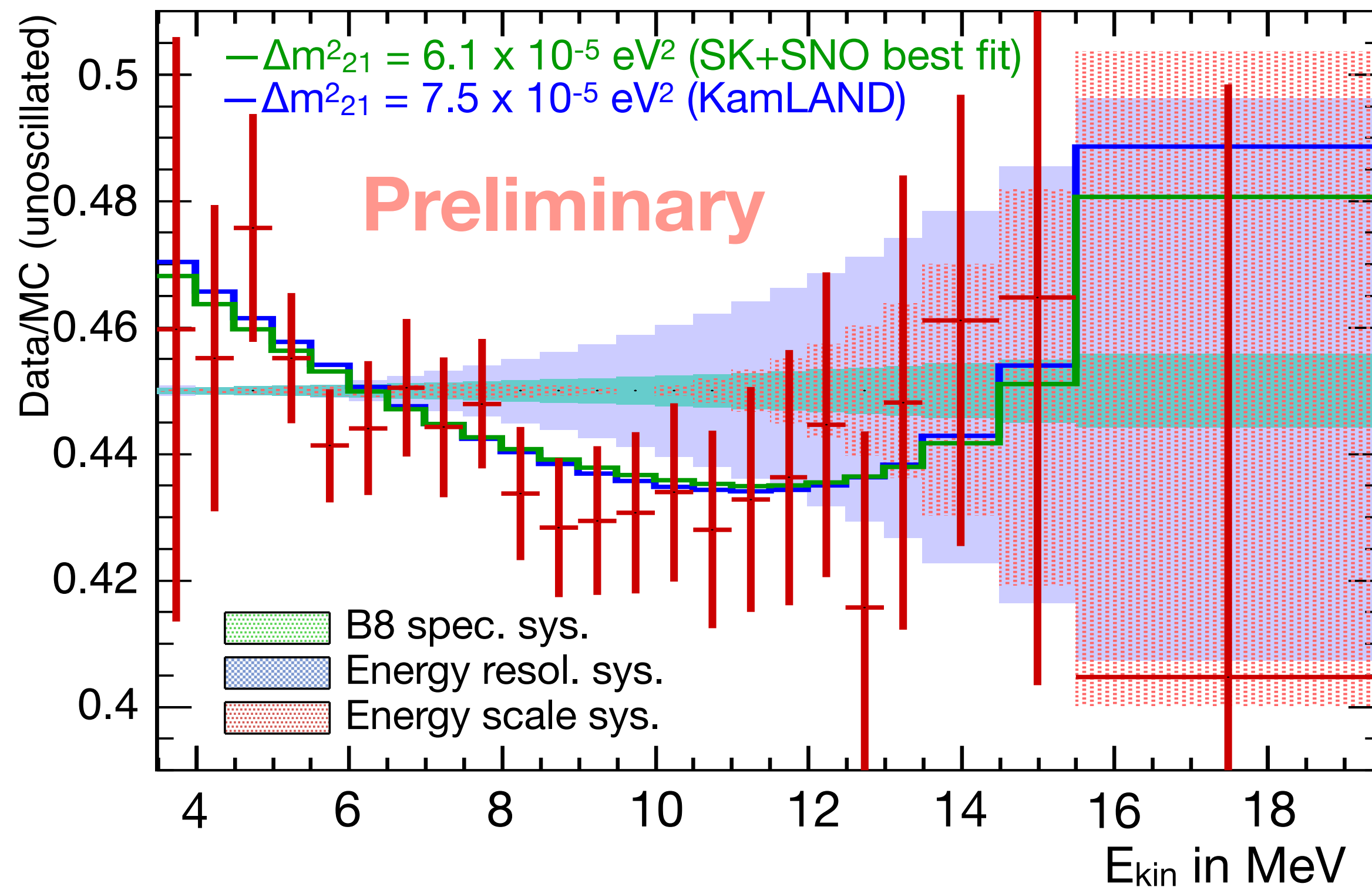
Solar neutrino flux

- Analysis using all the data up through SK-IV presented today

- 5805 live days from all (SK-I ~ SK-IV) period (2970 days in SK-IV)

- More than 100k ^{8}B (and HEP) solar neutrino interactions collected

Phase	Livetime [days]	Energy [MeV]	DATA/MC	Flux w/ systematic error [*10^6 /cm^2/sec]	Extracted Signal (Statistical only)
SK-I	1496	4.5-19.5	$0.453 \pm 0.005 \, ^{+0.016}_{-0.014}$	$2.38 \pm 0.02 \pm 0.08$	$22443 \, ^{+227}_{-225}$
SK-II	791	6.5-19.5	$0.459 \pm 0.010 \pm 0.030$	$2.41 \pm 0.05 \, ^{+0.16}_{-0.15}$	$7210 \, ^{+153}_{-151}$
SK-III	548	4.0-19.5	$0.459 \pm 0.010 \pm 0.030$	$2.40 \pm 0.04 \pm 0.05$	$8148 \, ^{+133}_{-133}$
SK-IV (Updated)	2970.08	3.5-19.5	$0.443 \pm 0.003 \pm 0.006$	$2.33 \pm 0.01 \pm 0.03$	$63890 \, ^{+381}_{-379}$
Combined	5805	–	$0.447 \pm 0.002 \pm 0.008$	$2.35 \pm 0.01 \pm 0.04$	More than 100k events

Oscillation analysis

Energy spectrum fit (SK-IV)

$-\Delta m^2_{21} = 6.1 \times 10^{-5}$ eV^2 (SK+SNO best fit)
$-\Delta m^2_{21} = 7.5 \times 10^{-5}$ eV^2 (KamLAND)

Preliminary

B8 spec. sys.
Energy resol. sys.
Energy scale sys.

Data/MC (unoscillated)

E_{kin} in MeV

Disfavors flat oscillation probability by ~1σ

Spectrum shape compatible with KamLAND Δm^2_{21} (< 1σ)

Day/Night amplitude fit (SK-IV)

Preliminary

A_{DN}

— Expectation
— SK-IV data

$$A_{D/N} = \frac{\Phi_{day} - \Phi_{night}}{0.5(\Phi_{day} + \Phi_{night})}$$

Δm^2_{21}
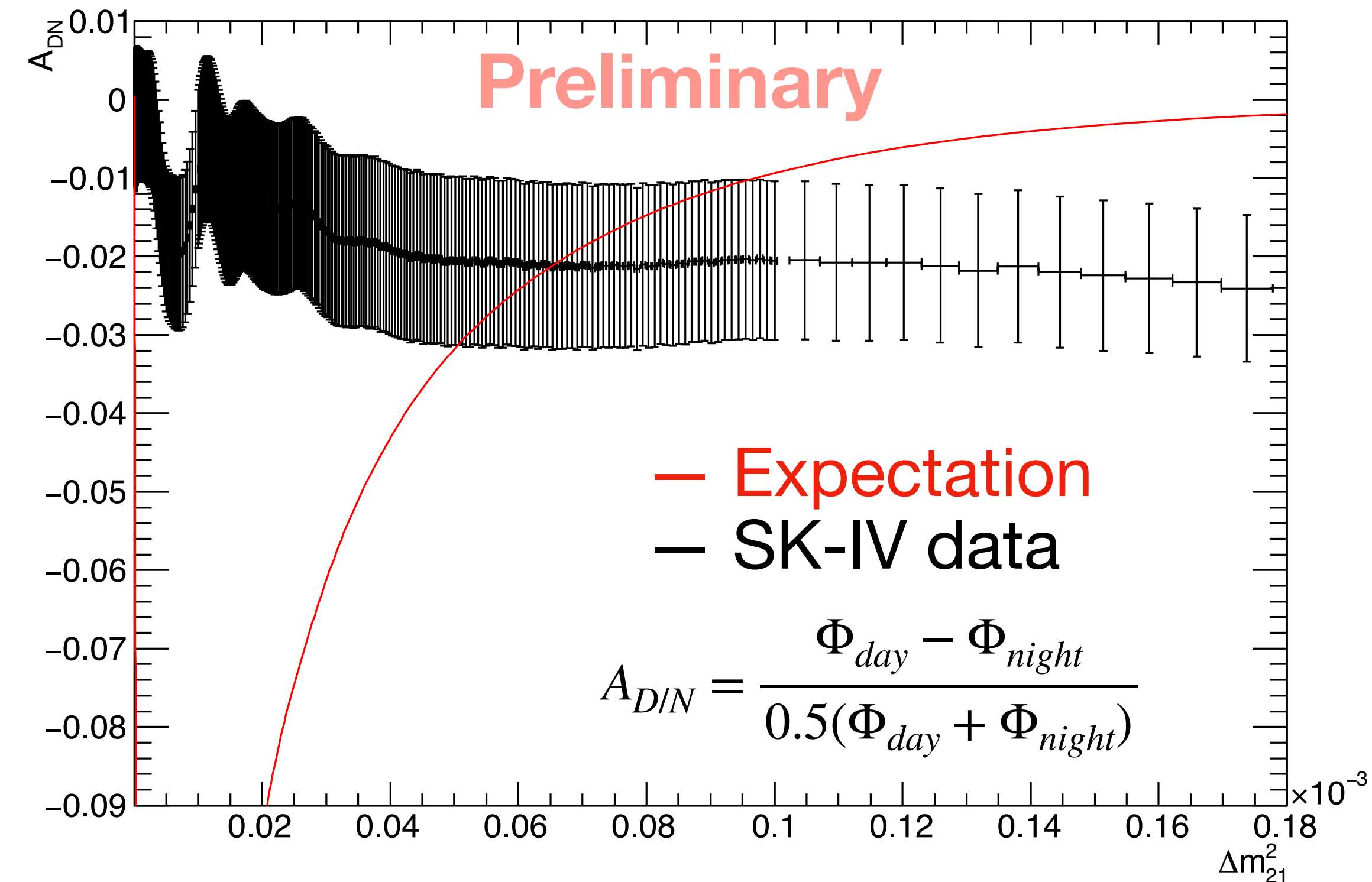
$A^{Fit}_{DN} = (-2.1 \pm 1.1) \%$ $[3.5 < E < 19.5 \text{ (MeV)}]$

~2σ preference of non-zero Day/Night asymmetry

Difference from the previous results

- Best fit value of solar Δm^2_{21} changed from 4.8×10^{-5} eV^2 (2019) to 6.1×10^{-5} eV^2

- Spectrum analysis:

  Data/MC ratio at E < 6 MeV slightly shifted upward

  - Shift of prediction due to improved detector simulation

  - Added statistics due to improved spallation cut

  - Event migration due to new reconstruction tool

- Day/Night asymmetry:

  $A^{Fit}_{DN} = (-3.6 \pm 1.6(stat) \pm 0.6(syst))\% \rightarrow A^{Fit}_{DN} = (-2.1 \pm 1.1)\%$

  - Event migration due to new reconstruction

  - Previous analysis used data up to Feb 2014 (SK-IV: 1664 days)

  - Added ~1200 days of data fluctuated towards smaller D/N asymmetry

- Both impacted to the shift of best fit Δm^2_{21} value by roughly equal amount (in term of change of $\Delta\chi^2$)
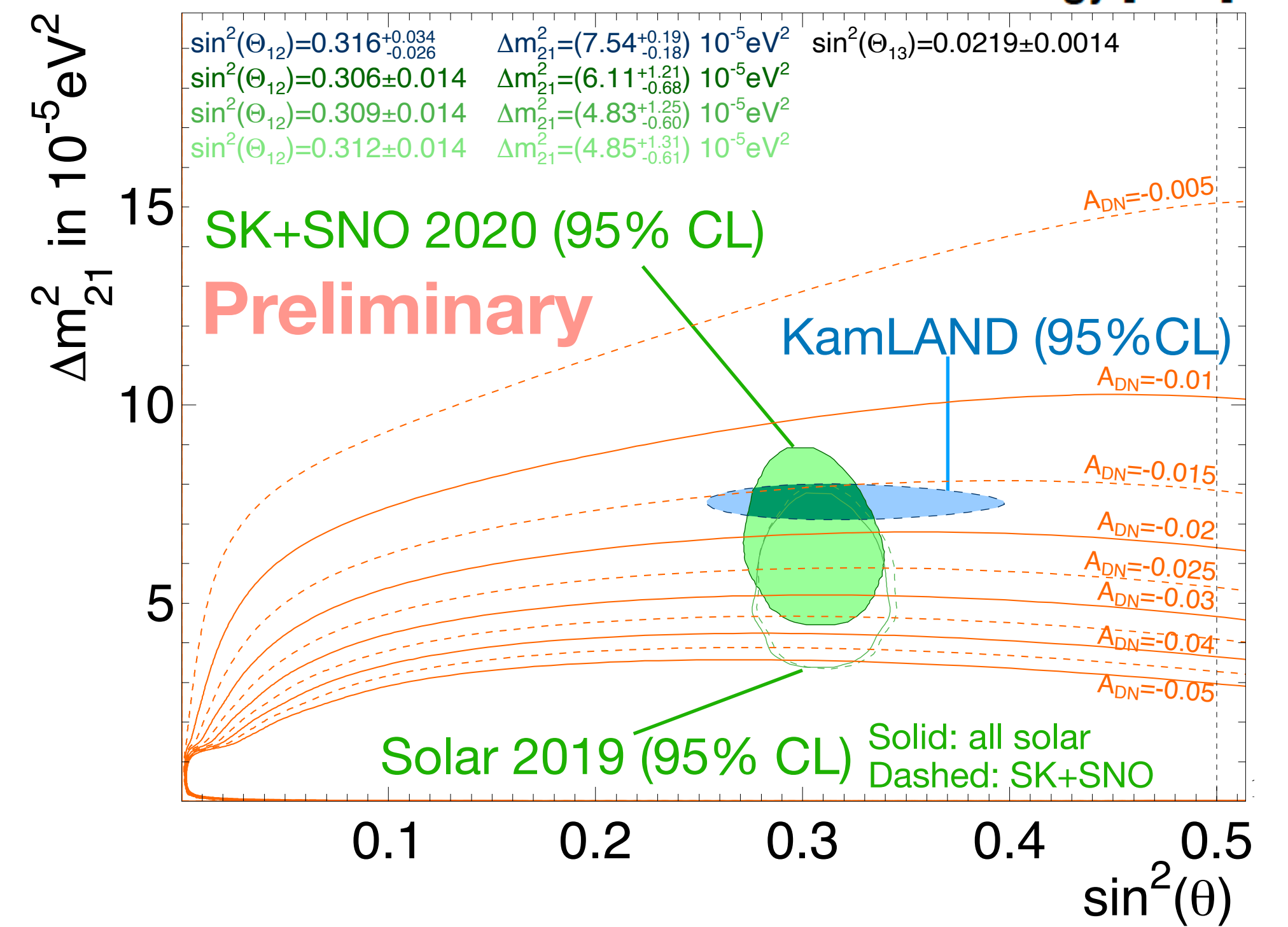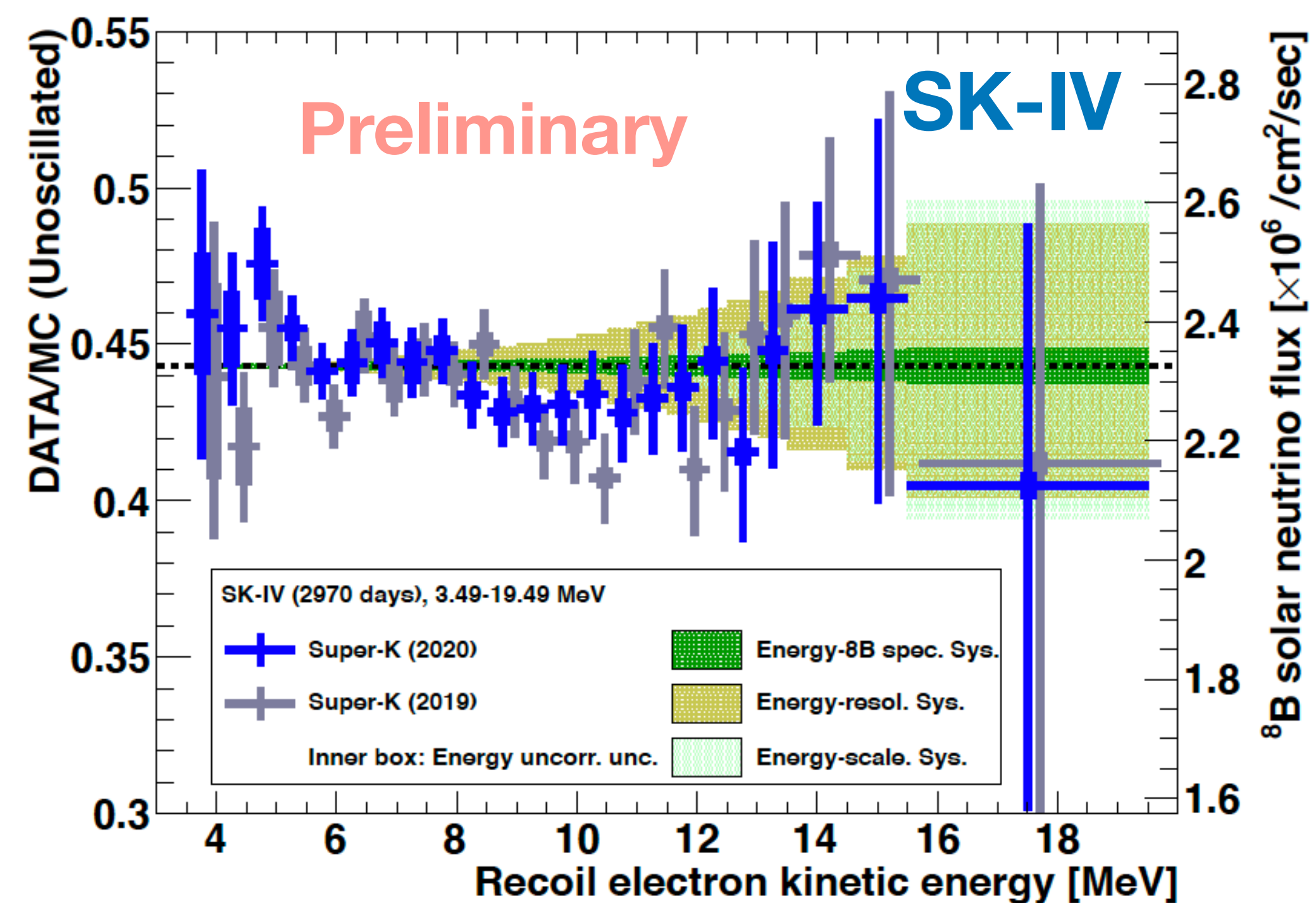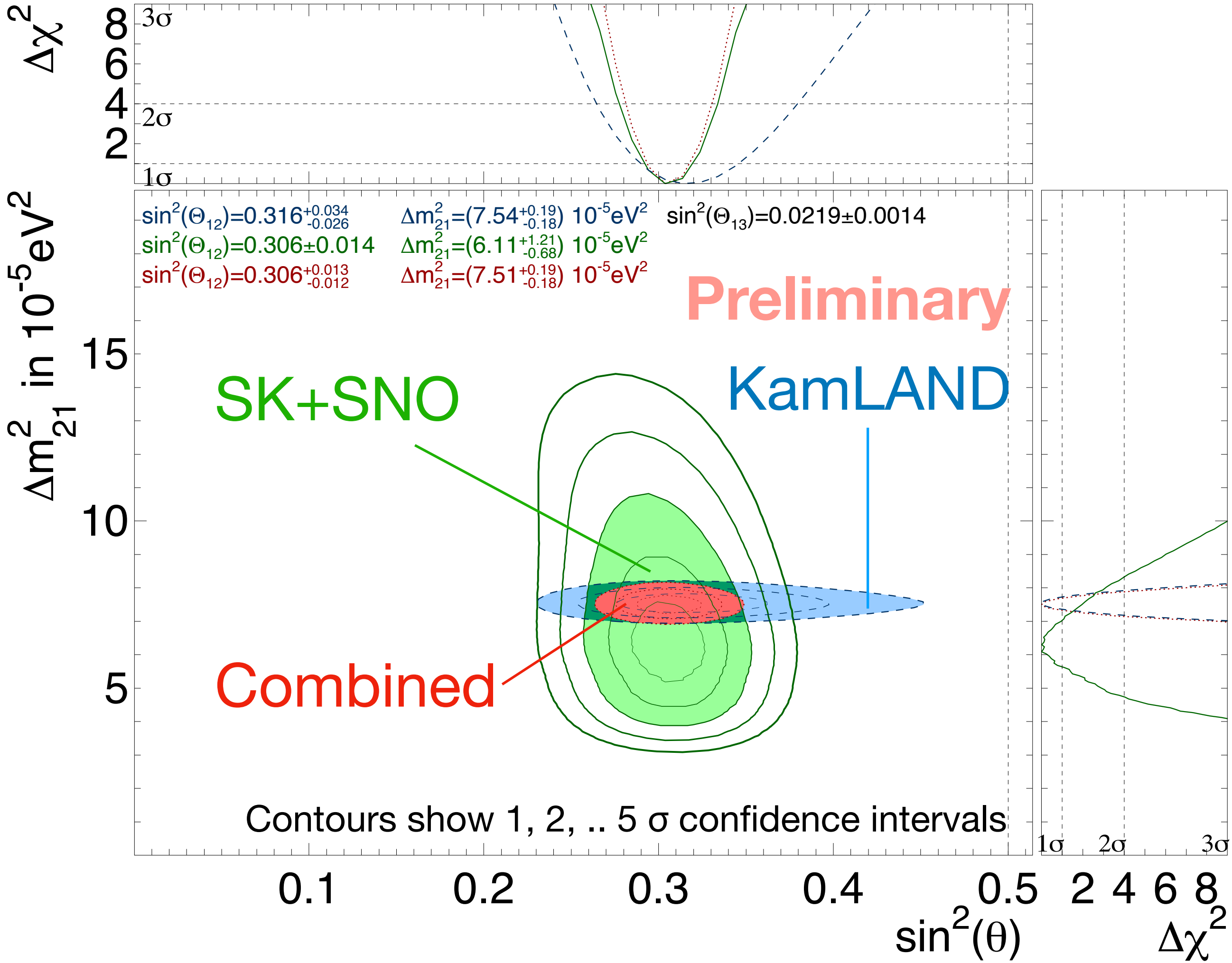
Oscillation Parameter Extraction

- Oscillation parameters extracted by combining all SK data, as well as SNO and KamLAND data

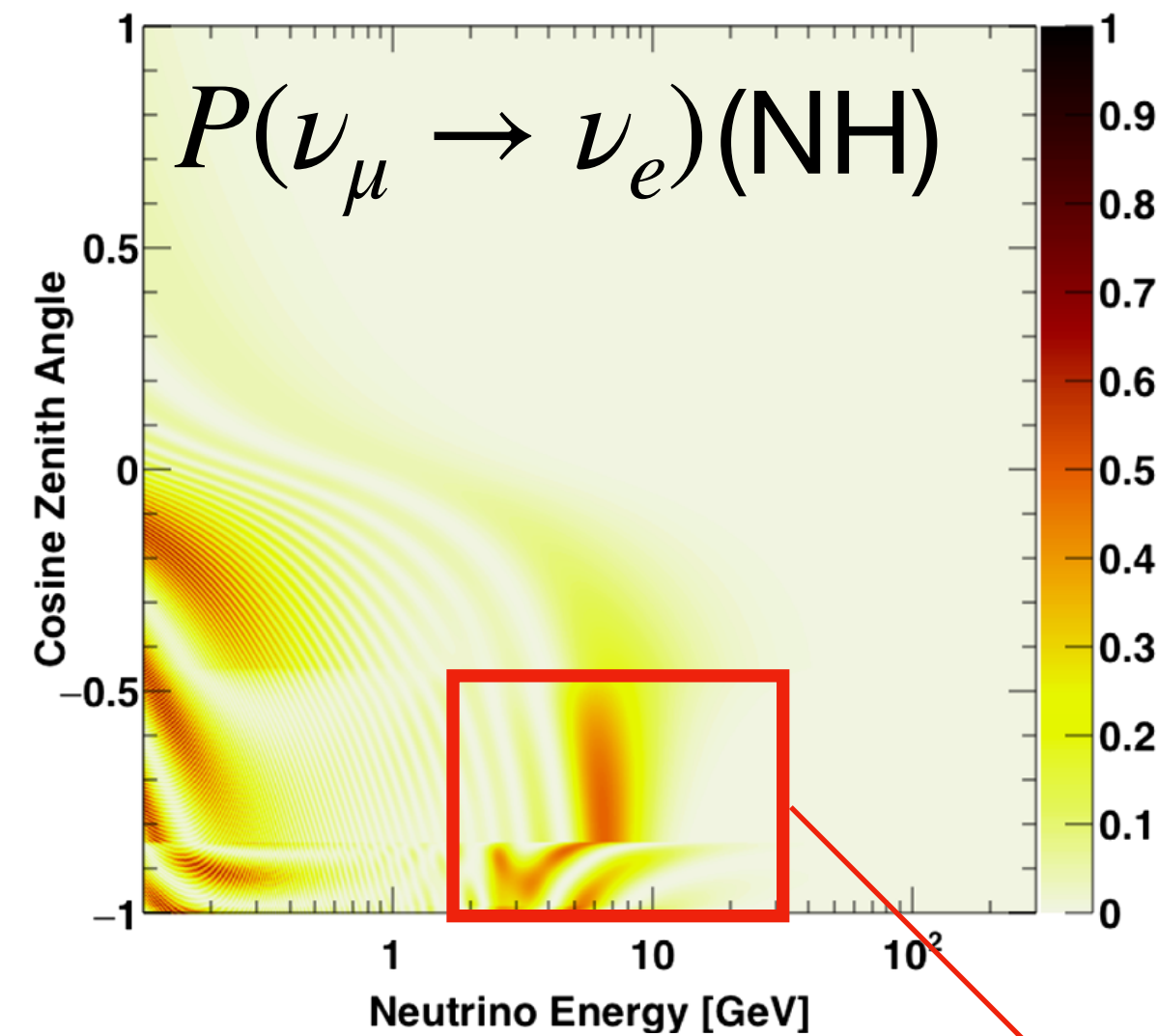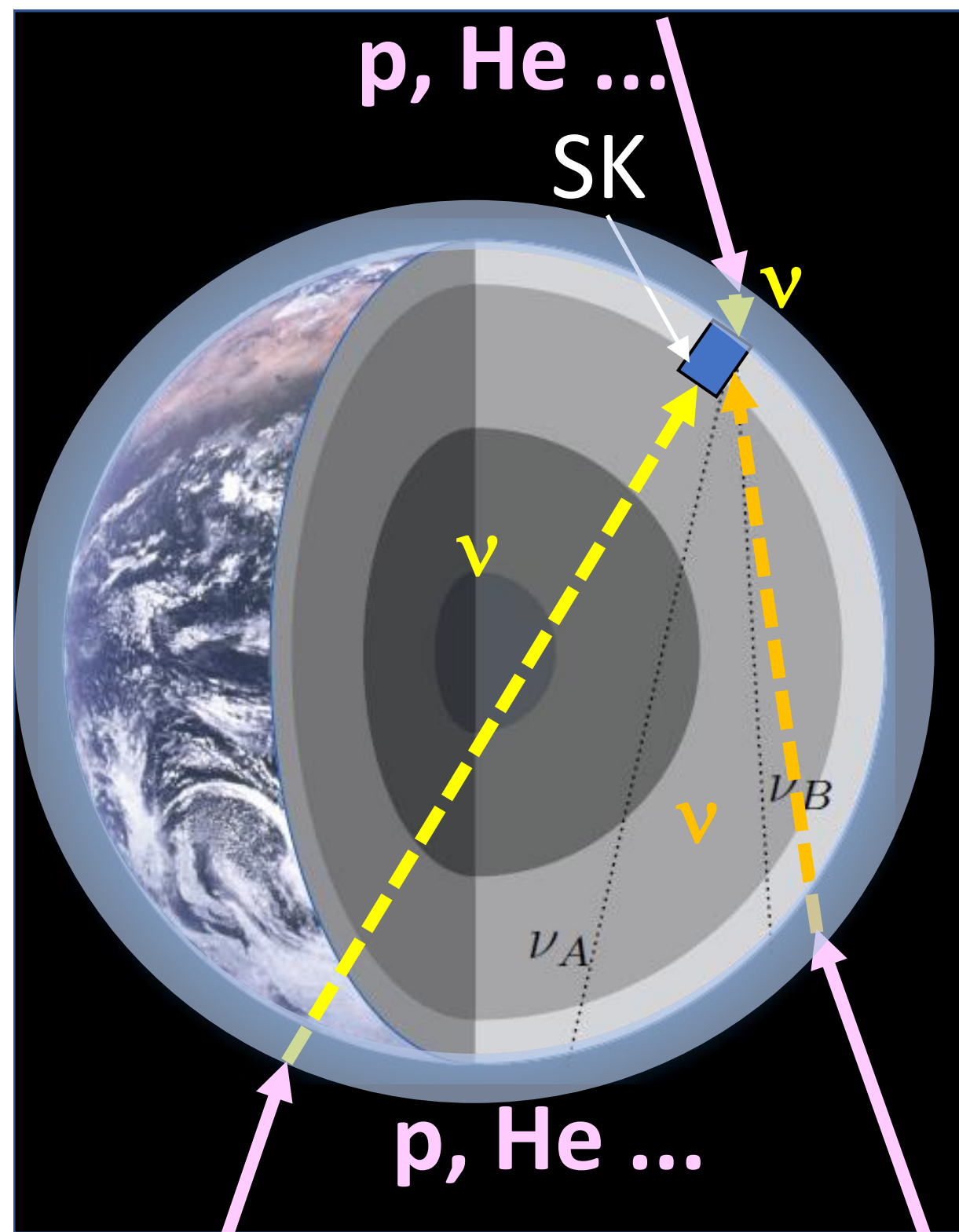|	$\sin^2(\theta_{12})$	Δm^2_{21} [10^{-5} eV^2]
KamLAND	$0.316^{+0.034}_{-0.026}$	$7.54^{+0.19}_{-0.18}$
SK+SNO	0.306 ± 0.014	$6.11^{+1.21}_{-0.68}$
Combined	$0.306^{+0.013}_{-0.012}$	$7.51^{+0.19}_{-0.18}$

- Consistent θ_{12} values among experiments

- Solar best fit Δm^2_{21} lower than KamLAND, but difference is less than the previous analysis.

SK+SNO fit disfavors the KamLAND best fit value at ~1.4σ (was ~2σ)

$\sin^2(\Theta_{12})=0.316^{+0.034}_{-0.026}$ $\Delta m^2_{21}=(7.54^{+0.19}_{-0.18})\ 10^{-5}$eV^2 $\sin^2(\Theta_{13})=0.0219\pm0.0014$
$\sin^2(\Theta_{12})=0.306\pm0.014$ $\Delta m^2_{21}=(6.11^{+1.21}_{-0.68})\ 10^{-5}$eV^2
$\sin^2(\Theta_{12})=0.306^{+0.013}_{-0.012}$ $\Delta m^2_{21}=(7.51^{+0.19}_{-0.18})\ 10^{-5}$eV^2

Preliminary

SK+SNO   KamLAND   Combined

Contours show 1, 2, .. 5 σ confidence intervals

$\Delta\chi^2$ Δm^2_{21} in 10^{-5} eV^2 $\sin^2(\theta)$ $\Delta\chi^2$

Atmospheric Neutrinos

Atmospheric Neutrinos

$P(\nu_\mu \to \nu_e)$(NH)

Matter effects

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$(NH)
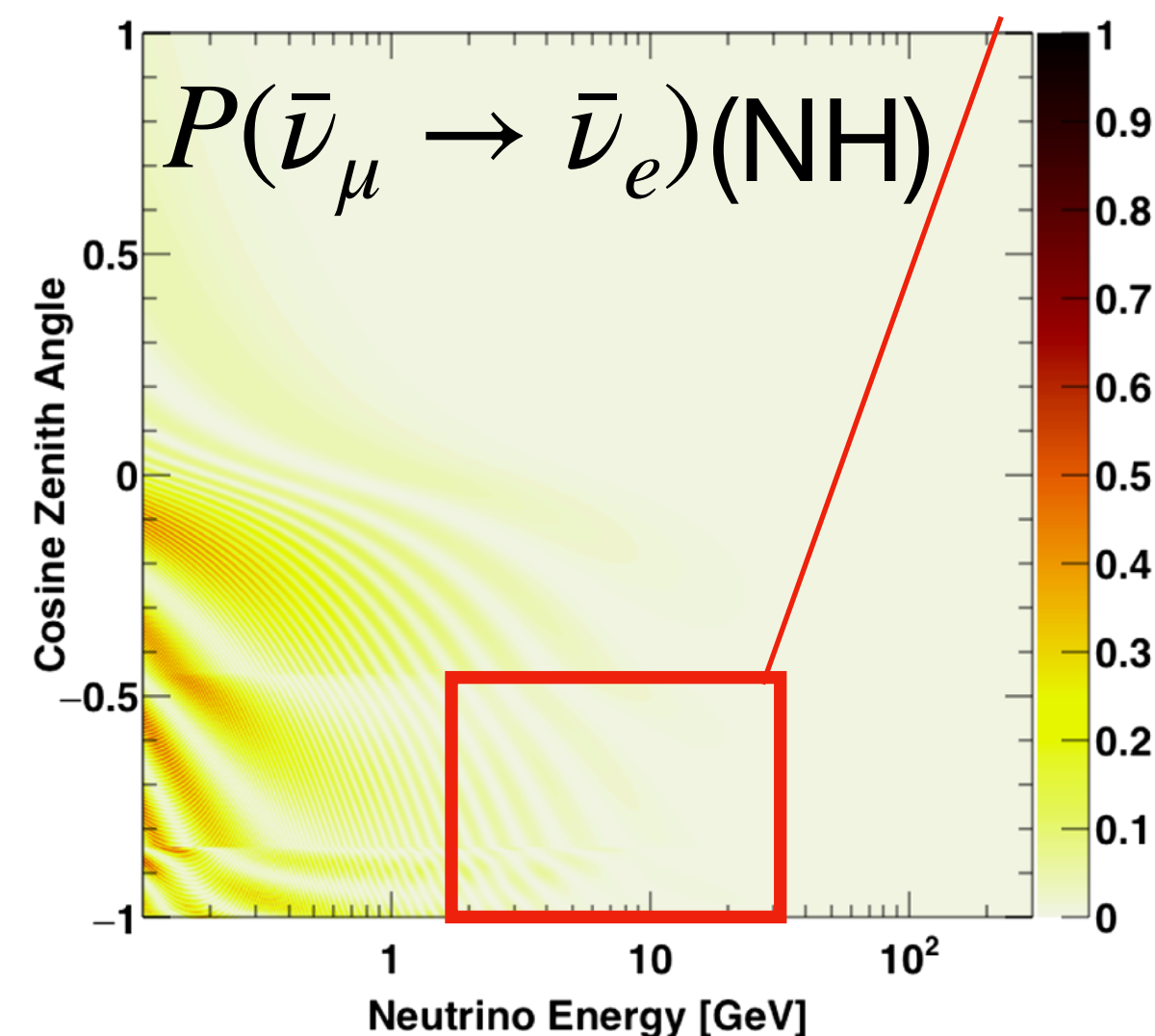
- Neutrinos produced by cosmic-ray interactions in earth's atmosphere

  - Baseline: O(10) km - O(10,000) km

  - Energy: peaks at several hundreds of MeV, extends to ~TeV

- Goals:

  - Δm^2_{32} and θ_{23} measurements: primary through $\nu_\mu/\bar{\nu}_\mu$ disappearance

  - CP violation parameter δ and mass-ordering: $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

Atmospheric Neutrino Analysis at SK

- New results using the full data sets from SK-I to SK-IV

  - Exposure: 364.8 kton-years

    (328 kton-years in Neutrino2018)

- Improvements in this analysis:

  - Neutron tagging (ε~25%) for $\nu/\bar{\nu}$ separation

  - New BDT-based event selection for multi-ring events

   - Increased signal efficiency and purity

Up: cosθ < -0.4, Down: cosθ > 0.4

Preliminary
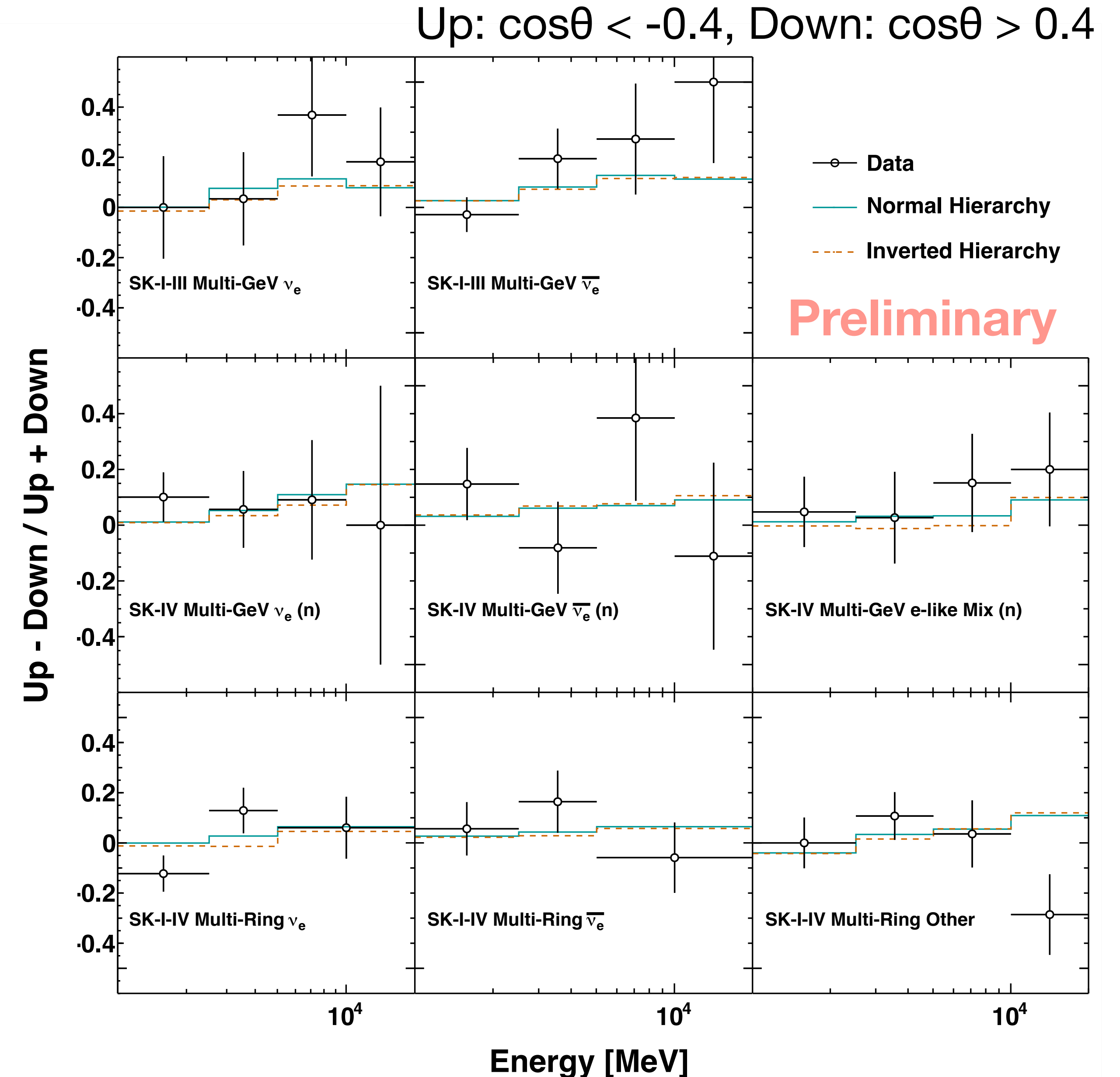
Oscillation Parameter Measurement
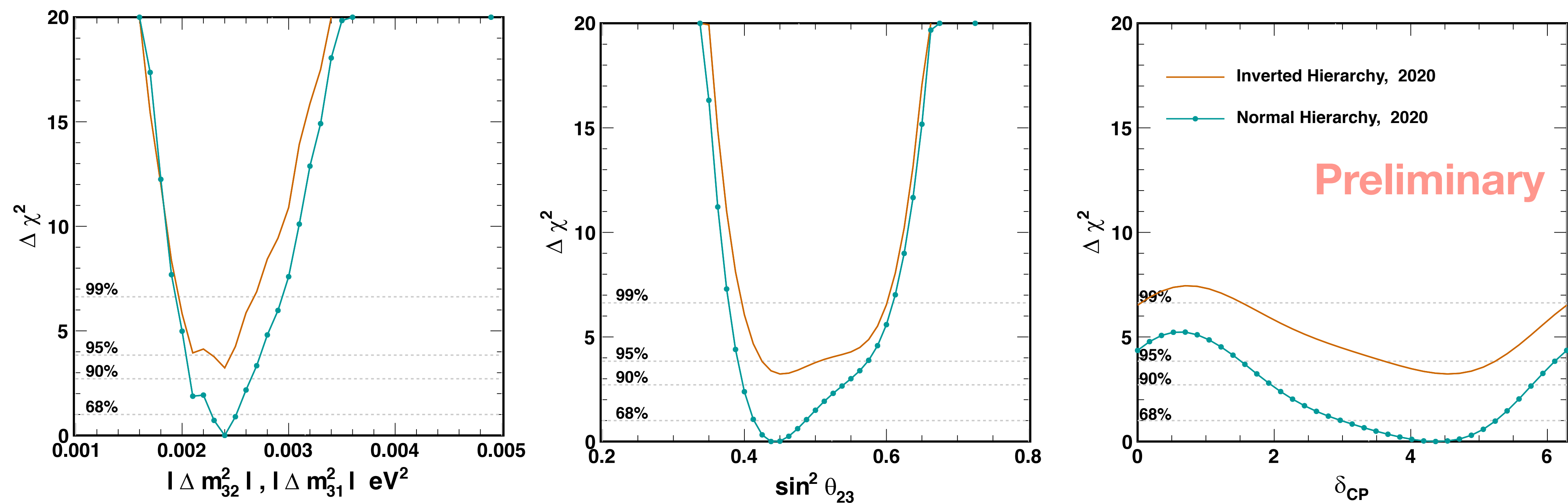
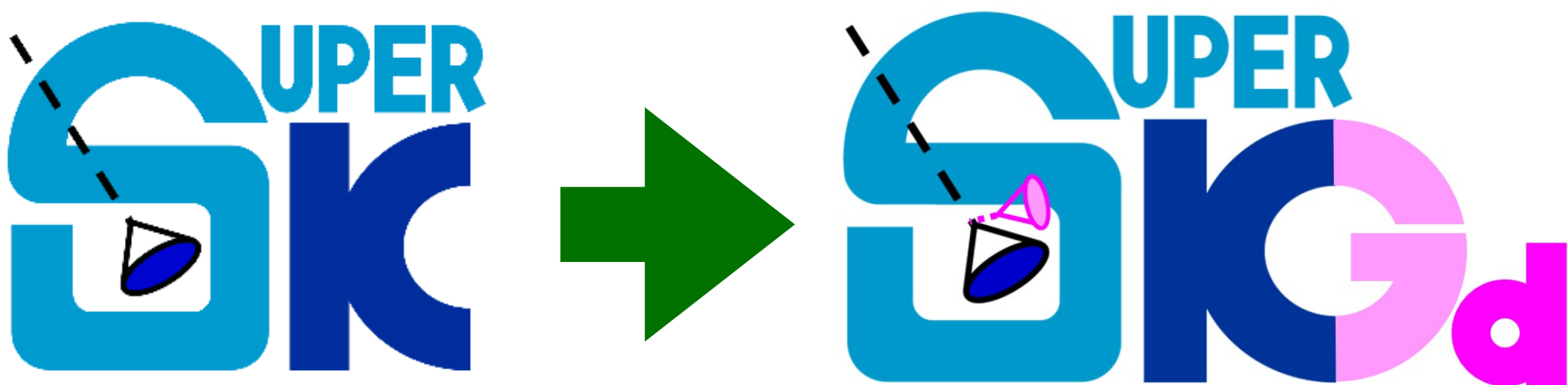| 930 Bins	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK (NH)	**1037.5**	0.0218	$4.36^{+0.88}_{-1.39}$	$0.44^{+0.05}_{-0.02}$	$2.40^{+0.11}_{-0.12}$
SK (IH)	**1040.7**	0.0218	$4.54^{+0.88}_{-1.32}$	$0.45^{+0.09}_{-0.03}$	$2.40^{+0.09}_{-0.32}$

SK data disfavors Inverted Hierarchy at 71.4-90.3% CL$_S$ (was 81.9-96.1% in 2018)

Also prefers: 1st θ_{23} octant and δ_{CP}~3/2π

Δm²₃₂ vs sin²θ₂₃ constraints
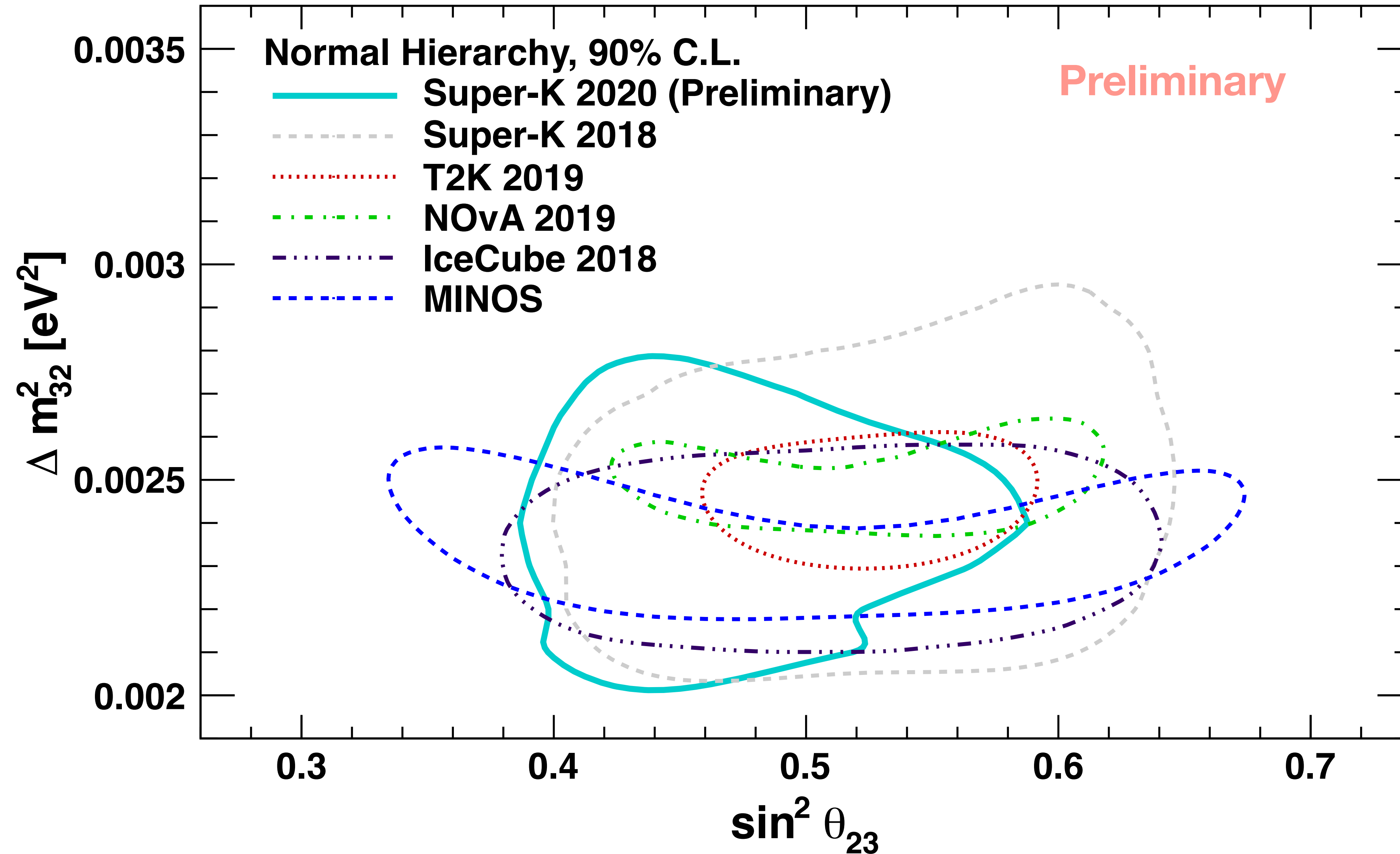
Summary

- The new era of Super-Kamiokande, SK-Gd, is about to start

- New results from Super-Kamiokande:

  - Diffuse supernova background search: New limit within a several factors of many models

  - Solar neutrino measurements: New spectrum and Day/Night asymmetry measurements to test MSW

  - Atmospheric neutrino measurements: New constraints on Δm^2_{32}, θ_{23}, δ_{CP} and MO

- Please also enjoy more results from Super-Kamiokande at the poster sessions:

ID	Title	Presenter	Session
43	Neutron-antineutron oscillation search at Super-Kamiokande	Linyan Wan	3
85	Search for astronomical neutrino from the Gamma-ray burst with Super-Kamiokande	Masayuki Harada	2
136	Long time supernova simulation and supernova burst search at Super-Kamiokande	Masamitsu Mori	2
161	Follow-up of Gravitational Wave events with Super-Kamiokande	Mathieu Lamoureux	1
166	Spallation Studies in Super Kamiokande	Scott Locke	2
175	Study of the atmospheric neutrino background for Supernova Relic Neutrino search	Seiya Sakai	4
221	Reactor Neutrinos in Super-Kamiokande	Alexander Goldsack	1
231	The diffuse supernova neutrino background in Super-Kamiokande	Sonia El Hedri	3
350	Latest solar neutrino analysis results from Super-Kamiokande	Yuuki Nakano	4